BRITISH WELDING * RESEARCH ASSOCIATION

VOL. 5. OCTOBER, 1951 No. 5

WELDING RESEARCH

PRICE FIVE SHILLINGS

Published by
BRITISH WELDING RESEARCH ASSOCIATION · 29 PARK CRESCENT · LONDON · W.1

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BRITISH WELDING RESEARCH ASSOCIATION

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IN THIS ISSUE

Research Report on "Fatigue Strength of Panels with Welded Angle Stiffeners," by R. Weck, Ph.D.

Fatigue tests by the resonance method have been carried out on 66 specimens consisting of a steel plate 5/16 in. thick measuring 10 ft. by 2 ft. stiffened with two welded-on or riveted-on angle or channel stiffeners 6 in. by 3 in. by 5/16 in., incorporating various welded details and joints. The stress distribution in the specimens was determined by electric resistance strain gauges, both in the longitudinal direction of the specimen for its whole length and for the central cross section where the bending stresses were a maximum.

Unjointed stiffeners welded to the plating by continuous fillet welding, intermittent staggered fillet welding and chain fillet welding, as well as continuous scalloped stiffeners and stiffeners with drilled holes in the flanges were tested. Butt welds in the stiffeners made with different types of electrodes with the reinforcement left on and the reinforcement removed, as well as several butt welded specimens made in shipyards under conditions of production and incorporating flaws were tested.

The effectiveness of several different types of reinforcing straps was investigated with the object of finding out whether the fatigue strength of butt welds can be improved by the use of such straps. Only one type of strap, which is not

practical in the shipyard because of the very large expenditure of workmanship required, was found to be an effective reinforcement of good quality butt welds. One other type of strap was found to be an effective reinforcement for poor quality butt welds. It was also found that drilling holes in the outstanding flanges of a stiffener reduced the fatigue strength by more than it is reduced even by a poor quality butt weld.

The report was prepared for the Shipbuilding Panel of the FE.8 Committee on Behaviour of Welded Structures under Dynamic Loading. The members of the Panel were as follows:

Mr. J. Turnbull (*Chairman*)	Lloyds Register of Shipping
Mr. F. C. Cocks ..	Lloyds Register of Shipping
Mr. E. Cuthbert ..	Harland & Wolff Ltd.
Mr. H. H. Hagan ..	Lobnitz & Co. Ltd.
Mr. H. T. Johnson ..	Naval Construction Department, Admiralty
Mr. D. M. Kerr ..	Alexander Stephen & Sons Ltd.
Mr. J. Lenaghan ..	Wm. Gray & Co. Ltd.
Mr. L. Redshaw ..	Vickers-Armstrong Ltd.

Technical Secretary: R. P. Newman

ASSOCIATION NOTES

New Automatic Welder

An automatic welding head suitable for the mechanical welding of both light alloys and steels is being developed in the Association's Laboratories at Park Crescent. For the welding of light alloys the arc is struck between a bare filler wire and the work, the weld pool and arc column being shielded with argon. For experimental welding on steel ordinary covered electrodes are being used.

Unlike the self-adjusting arc process (Aircomatic type) the wire or electrode feed speed is controlled automatically from the arc voltage so that the arc length remains constant. A new form of control device is employed which has permitted welding over a wide range of wire feed speed up to 400 in. per minute. Various features of the apparatus, including the control circuit which is extremely simple and does not employ electronic devices, have been the subject of a recent patent application in the names of P. T. Houldcroft, J. G. Purchas and the British Welding Research Association.

The apparatus is being used for research on the welding of the alloys of magnesium and aluminium, and on alloy steels.

Ashorne Hill Summer School, 1952

As announced in our previous issue the Association is to hold its second Summer School at Ashorne Hill from 16th July until 25th July, 1952. It has been decided that the School should be arranged to make better provision for the different qualifications and interests of those concerned with welding, and on this occasion it will be divided into two parts. The first part, from Wednesday, 16th July, till Sunday, 20th July, will be for those interested with the practical aspects of welding, and the second part from Sunday, 20th July, till Friday, 25th July, will be for those concerned with design, inspection and manufacturing problems in welding. The second part of the School will comprise four separate groups, to run concurrently, and these will be arranged on a subjective basis as distinct from the principle of division by industries which was adopted at the school held earlier this year. The four groups will be formed as follows:

Group A—Metallurgy and Physics of Welding.

Group B—Testing and Inspection.

Group C—Design for Welding by Analysis and Ex-Experiment.

Group D—General Welding Engineering.

Further details of the programme and directions for application will be issued later.

New Members

Since 1st July, 1951, the following companies have joined the Association:

Ordinary Members

Peter Brotherhood Ltd.
Coventry Radiator & Presswork Co. Ltd.
Hawker Aircraft Ltd.
Hills (West Bromwich) Ltd.
The National Smelting Co. Ltd.
Rolls-Royce Ltd.
Tank & Industrial Plant Association.
P.A.M.E.T.R.A.D.A.
British Ropes Ltd.
B. & F. Carter & Co. Ltd.
R. Y. Pickering & Co. Ltd.
British Messier Ltd. } *Transferred from Associates.*
T. C. Jones & Co. Ltd. }

Associates

The Buckle Flame Cutter Co. Ltd.
The British Steel Piling Co. Ltd.
D. Napier & Son Ltd.

Wall Chart of Faults in Arc Welds

A few copies of the illustrated wall chart, showing common faults that can occur in the metal arc welding of steel, are still available from the Publications Department of the Association. The chart has 37 half-tone illustrations and is printed in two colours and backed with a heavy strawboard suitable for direct mounting to the walls of welding shops, offices, etc. Orders for copies of the chart should be addressed to the Publications Department, B.W.R.A., 29, Park Crescent, London, W.1. Price: 7s. 6d. each, post free.

R.73

FATIGUE STRENGTH OF PANELS WITH WELDED ANGLE STIFFENERS

A report of an investigation to determine the life of different types of welded joints in angle stiffeners attached to plates, when subjected to many repetitions of loading.

This report was first issued to members of the British Welding Research Association as a confidential document in November, 1950

By R. WECK, Ph.D.

INTRODUCTION

The construction and particularly the repair of ships frequently requires joints to be made in frames, beams and bulkhead stiffeners. Failures are experienced in such joints occasionally, when these are executed in the form of butt welds. These failures have the characteristic appearance of fatigue failures.

The investigation described in this report was carried out to determine the life of different types of welded joints in stiffeners when subjected to many repetitions of loading. The attachment of the stiffeners to the plating was also investigated.

The resonance method was used to carry out these fatigue tests with specimens consisting of stiffeners welded to plates with and without welded joints in the stiffeners. Most of the specimens were made in the laboratory. The joints in these specimens were made with such great care as could not normally be expected in the shipyard under conditions of production. A number of specimens, typical of present-day practice and fabricated in shipyards, were included in the series of tests.

DESCRIPTION OF TEST-PIECE

The specimens, of the cross section shown in Fig. 1, consisted of plates 10 ft. long, 2 ft. wide and 5/16 in. thick. Two angle stiffeners 6 in. by 3 in. by 5/16 in., or in the case of the riveted specimens two channels 6 in. by 3 in. by 5/16 in. were attached to the plates either by continuous or intermittent fillet welds or by riveting. In order to obtain a symmetrical cross section with the two principal axes of inertia parallel and normal to the plane of the plate, the angles were attached opposite hand at 12 in. distance. Each specimen weighed approximately 440 lbs. The neutral axis of the section was 1·85 in. above the outside surface of the plate and the moment of inertia about the principal axis parallel to the plane of the plate was 71·9 in.^{4}.

Most of the specimens had stiffeners with a welded joint of one type or another in the middle. There were no joints in any of the plates.

CHEMICAL COMPOSITION AND PROPERTIES OF THE MATERIAL

The specimens were constructed from mild steel to B.S.13. The steel was obtained from the current production of a steel works which manufactures a large quantity of steel for use in shipbuilding.

The chemical composition of the plates and angle material were as follows:

	Plate per cent.	*Angle per cent.*
Phosphorus	·033	·013
Sulphur	·075	·040
Silicon	trace	·04
Manganese	·460	·620
Carbon	·108	·184
Copper	·095	·278
Nickel	·120	·320
Arsenic	·030	·032
Tin	·018	·030
Chromium	·042	·038
Molybdenum	·025	·040
Nitrogen	·0035	·0050
Aluminium	·004 = 1·4 ozs./T	·005 = 1·8 ozs./T
Alumina	·002 = 0·4 ozs./T	·002 = 0·4 ozs./T
	1·8 ozs./T	2·2 ozs./T

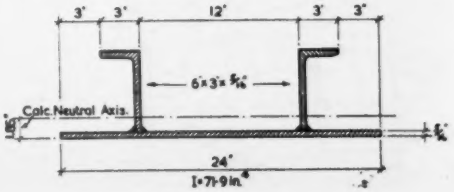


Fig. 1. Cross-section of specimen.

The mechanical properties of the material were as follows:

	Plate	*Angle*
Ultimate tensile strength	25·8-26·04 (tons sq. in.)	29·8-32·4 (tons sq. in.)
Yield stress (upper)	19·2 (tons sq. in.)	20·4-20·8 (tons sq. in.)
Yield stress (lower)	17·4-17·6 (tons sq. in.)	19·7-21·2 (tons sq. in.)
Per cent. elongation (2 in. gauge length)	37-38	33-39
Per cent. reduction of area	62-71	62-67
Vickers hardness variation ..	108-129	130-149

The McQuaid-Ehn grain size was the same for both the angle and the plate material, namely, 1 to 5, mostly 2. Typical micro-sections of the plate material and the angle material are shown in Figs. 2 and 3.

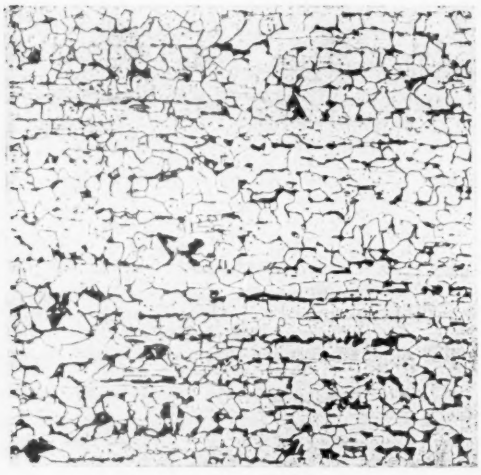


Fig. 2. Microstructure of plate material. ×200

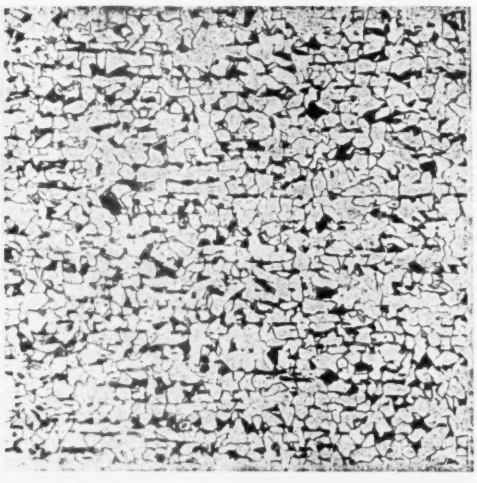


Fig. 3. Microstructure of angle material. ×200

FABRICATION OF SPECIMENS

In order to ensure that the number of flaws in the butt welds of the stiffeners was kept to a minimum, the joints in the stiffeners were made before the stiffeners were attached to the plating. All welding was done in the downhand position.

The ends of the angle stiffeners were chamfered in a shaping machine to a 60 deg. Vee, with the wider part of the Vee on the outside of the angle. The gap and root face were 1/32 in. The butt weld was made with three runs in each leg of the angle, in the sequence indicated in Fig. 4. Runs 1 and 4 were made with 10 G electrodes, the remaining runs with 8 G electrodes. The back of the angle was then chipped out to nearly half its thickness and this was filled with another run from an 8 G electrode. This left a point of poor penetration at the heel of the angle where the material is thickened by the angle fillet. In the first few specimens (Nos. C1 to C4, C11 and C12) a conical hole was made at this point after completion of the joint and this was filled with weld metal. This procedure was unsatisfactory and in later specimens (Nos. C21 to C24 and C31 to C34) the inside of the angle at the heel was chipped out at right angles to the direction of the butt weld for a distance of approximately 1½ in. and this was then filled with a weld crossing the main butt weld at right angles. This procedure eliminated the inevitable flaws which were left at this point when using the first procedure.

The straps for the specimens in which the butt weld was reinforced by a strap were also attached before the stiffeners were welded to the plating. The fillet welds attaching the straps to the angle were stopped ½ in. short at each side of the butt weld. Before attaching the straps the butt welds were ground flush.

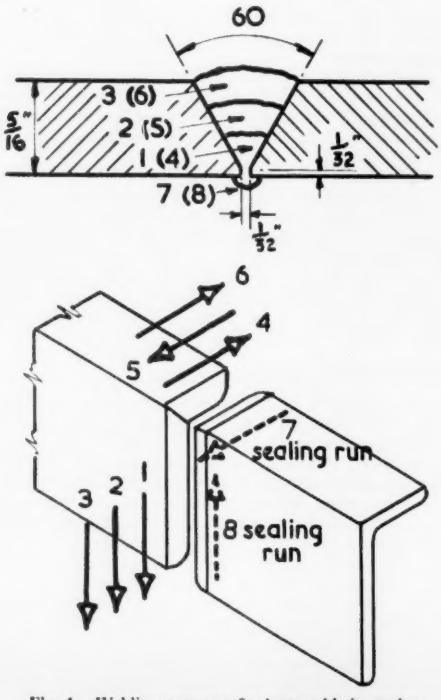


Fig. 4. Welding sequence for butt welds in angles.

The fillet welds attaching the straps were of unequal leg length and were carefully filed with a rotary file after welding to eliminate all traces of undercut and to produce a smooth contour. A macro-section of one of these fillet welds is shown in Fig. 5.

The end of the butt weld in the longer leg of the angle stiffener which was welded to the plating was cut out with a saw producing a 2-in. diameter semicircular scallop, in order to avoid crossing the butt welds with the fillet welds, by means of which the stiffeners were attached to the plating.

In order to reduce distortion to a minimum all specimens were made in pairs. The stiffeners which had been joined and drilled were bolted to two simple jigs, one at each end, which ensured that the distance between the two stiffeners was strictly maintained during welding and that holes necessary for the attachment of the testing gear were in proper alignment after welding.

Two stiffeners thus bolted together were first tack welded to the plate. Two plates with their stiffeners attached by tack welding were then firmly clamped together back to back all round the plate edges; loose distance pieces were inserted in between each pair of stiffeners every 18 in. or so along the length of the specimens, and these distance pieces were kept in position by clamps placed over both stiffeners. The two specimens were then placed into two large clamps, one at each end, which were provided with trunnions permitting the two specimens to be rotated about their longitudinal axis so that all fillet welds could be deposited in the tilted position. It was important that the specimens should not be distorted after welding because distortion would have resulted in certain difficulties in testing. By following the proper welding sequence in the deposition of the fillet welds, this method of construction resulted in specimens which were almost perfectly straight, despite the fact that most of the plates and angles were initially curved. Two specimens assembled for welding are shown in Fig. 6.

It may be noted that very high residual and reaction stresses were undoubtedly introduced in these specimens during construction and severe plastic deformations took place during welding in the vicinity of the welds. This became visible when Lüders lines appeared in some of these specimens after they had been accidentally exposed to moisture. A typical pattern of Lüders lines in the vicinity of the welds where the scale had flaked off in consequence of the plastic deformation produced by welding is shown in Fig. 7.

Most of the stiffeners were attached by intermittent fillet welds of 5/16 in. nominal leg length, but some specimens were attached by continuous fillet welds of 3/16 in. nominal leg length. These continuous fillet welds, however, were not deposited by welding continuously from the centre outwards

Fig. 6. Two specimens clamped back to back. Assembled for the welding of the stiffeners to the plating.

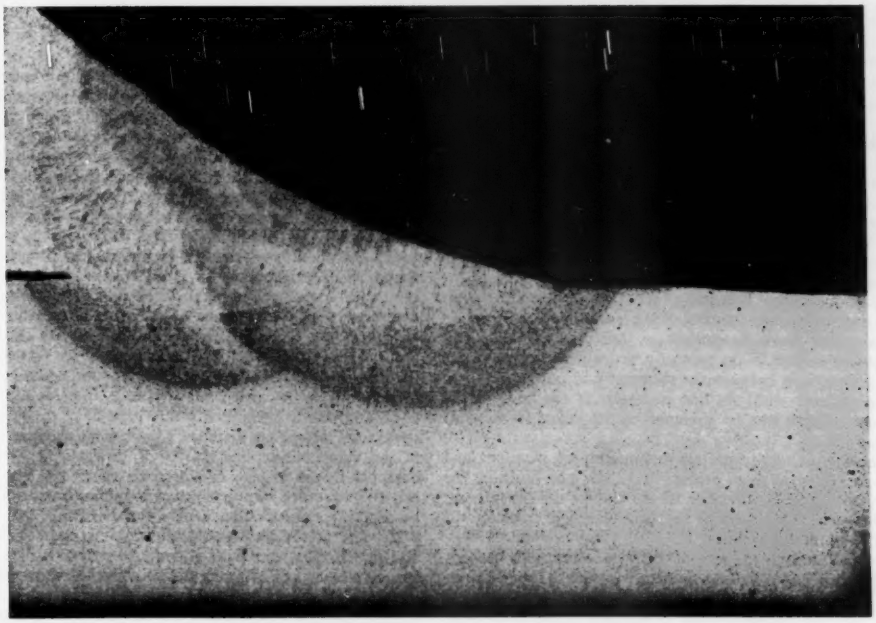


Fig. 5. Macrosection of fillet weld attaching strap.

Fig. 7. Typical pattern of Lüders lines in the vicinity of the welds attaching stiffeners to plating on the reverse side of the plates.

or from one end of the stiffener to the other, but by a step back method and by alternating between one specimen and the other in order to keep the shrinkage on both sides of the centre plane equal. Very accurate records of the whole welding procedure and sequence were kept for each specimen. The edge of the angle was not machined and the particular angles supplied for this investigation had edges considerably sharper than those of the B.S. profile. The arrangement of the welds is shown in Figs. 8a, b and c.

RADIOGRAPHIC EXAMINATION

The first 20 specimens were very carefully examined radiographically at the radiographic laboratory at H.M. Dockyard, Chatham. The following is quoted from the radiography report:

"*Surface Undercutting*. There was little evidence of this defect in any of the welding examined. It was nowhere more than occasional in extent and slight in nature.

Porosity. This defect generally appeared as a few faint spots well distributed through the welding. Only one instance of a small localised group of spots was apparent.

Inclusions. A line inclusion was evident at the root of all the fillet connections between the stiffeners and base plates. From its position relative to the weld this line inclusion appeared to be under the toe of the stiffener and was presumably anticipated, therefore, from the edge preparation and method of welding employed. In a number of intermittent fillet welds there was evidence of a small slag patch close to the end of the welding, and this should generally have been visible on the surface.

Inclusions in the butt joints generally appeared as short faint lines at or near the root of the weld.

Incomplete Root Penetration or Lack of Fusion. This defect was evident in the root of practically the whole of the fillet connections between the stiffeners and base plates, and was associated with the line inclusion at the root of the stiffeners. There was no evidence of the defect in the butt joints.

Cracking. Cracks were evident in eighteen positions and were suspected in three others. In all but one position, the crack was either at or close to the end of the intermittent connection between stiffener and base plate. No cracking was revealed in the butt joints."

The inclusions at the root of the fillet connections between the stiffeners and the plates and the incomplete root penetration were undoubtedly due to the fact that the edge of the angle was not machined prior to welding. These faults were inevitable with angles having rather sharp edges.

The cracks at the ends of the intermittent fillet welds were presumably crater cracks.

When the tests with the specimens which had been radiographically examined had been concluded, the fatigue failure could in no case be related to the radiographic findings pertaining to the particular specimen.

In some of the specimens with machined butt welds the failure started from an inclusion at the heel of the angle which was inevitable with the procedure employed for these first specimens, but this flaw would not be revealed in radiographic examination because of the changing thickness of the angle at the heel. The remaining specimens tested in this series of experiments were not examined radiographically because no correlation whatsoever had been established between the fatigue failure of the first twenty specimens and the radiographic findings.

OBJECT AND SCOPE OF INVESTIGATION

The maximum stress range to which any part of a ship structure is subjected repeatedly in service is not known very accurately. There is even considerable doubt whether the cyclic component of the service stresses in a ship structure attains high enough values often enough for the possibility of fatigue failure to be considered, although failures exhibiting the characteristic appearance of fatigue fractures have been observed in ships. Since the service stresses in ships are not accurately known, the determination of the absolute endurance limits for different types of details in terms of tons per sq. in., by means of S-N curves, is of little use. It is useful to know, however, in what order different types of joints will range according to their fatigue endurance. To determine this order was the object of the present investigation. For the determination of absolute values of fatigue limits, a fairly large number of tests is required. To determine the fatigue limit of only one type of joint would require fatigue tests to be carried out at least at three or four stress levels and several specimens would have to be tested at each stress level in order to arrive at a reasonable average, in view of the very considerable scatter of results which must be expected in the testing of full scale structures and which cannot be avoided completely even in fatigue tests with small, homogeneous and polished, metal test pieces.

In view of the limited objective of this investigation, it was hoped that tests with only four specimens of each of five different types of joints would be sufficient to establish the correct order of endurance. It was decided to test two or three of the four specimens at a stress range of ± 8 tons per sq. in. and the remaining one or two at a lower range. The

stress range of ± 8 tons per sq. in. was chosen because it was thought that higher stresses than ±8 tons per sq. in. would not occur in a ship with sufficient frequency to give rise to fatigue failure.

It was envisaged at the beginning to test five different types of specimens and to extend the investigation in the light of results obtained with these specimens. The five different types of specimens were as follows:

Specimens Code Letter A. Unjointed continuous stiffeners welded to the plating with continuous fillet welds.

Specimens Code Letter B. Unjointed continuous stiffeners welded to the plating with staggered intermittent welds of 3 in. length at 7 in. centres. The arrangement of the fillet welds for these specimens is shown in Fig. 8a.

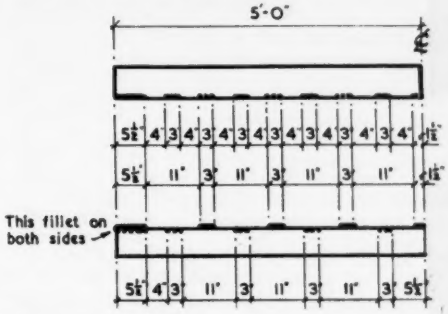


Fig. 8a. Arrangement of intermittent fillet welds (Staggered). *Specimen type* "B."

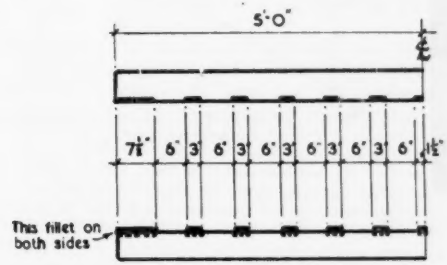


Fig. 8b. Arrangement of intermittent fillet welds (Chain). *Specimens type* "I" and "H."

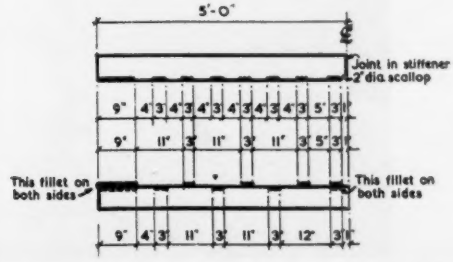


Fig. 8c. Arrangement of intermittent fillet welds (Staggered). *Specimens type* "C," "D," "E," and "K."

Specimens Code Letter C. Stiffeners joined at the centre by a butt weld and welded to the plating by intermittent staggered fillet welds. The reinforcement of the butt weld to be removed by grinding. The arrangement of the fillet welds is shown in Fig. 8c and the appearance of the butt weld on the outside and on the inside of the angle is shown in Figs. 9 and 10 respectively.

Specimens Code Letter D. Stiffeners joined with butt welds in the middle, the butt weld being reinforced with a rectangular strap of the dimensions shown in Fig. 11, attached with end fillet welds and side fillet welds. The fillet welds attaching the rectangular strap were dressed with a rotary file. A gap was left in the side fillet welds in the way of the butt weld as shown in Fig. 12.

Specimens Code Letter E. Stiffeners joined by a butt weld in the middle, the butt weld being reinforced by a diamond-shaped strap of the shape and dimensions shown in Fig. 13, attached by fillet welds all round, leaving a gap only in the way of the butt weld as shown in Fig. 14. The fillet welds attaching the strap were dressed with a rotary file.

It was realised, of course, that the dressing of the fillet welds is not practicable in the shipyard, but it was decided, nevertheless, to dress these fillet welds in order to eliminate in this first investigation any accidental effects due to differing quality and shape of the welds. Moreover, if the fillet welds were machined, the results would indicate the absolute optimum endurance that could be realised by the use of straps of this type, and it was desired to know in the first place, this optimum in relation to other types of joints.

Specimen Code Letter F. Two of the specimens of type A were unbroken after considerably more than 10,000,000 loading cycles and the third specimen lasted for a number of cycles well in excess of that obtained for any other type of specimen, so that only three specimens of type A were actually tested. The fourth specimen which had been made was subsequently cut through the stiffener with a saw and a rectangular strap of the form and dimensions shown in Fig. 15 was attached by ordinary unmachined fillet welds to the flanges of the angle stiffener over the unwelded gap. This specimen was given the code letter F.

Specimens Code Letter G. The test with one of the specimens of type B had to be discontinued because of a mechanical fault of the testing gear and a second specimen which had been made was not tested because the results obtained for the other two specimens were so close together and so far above the results obtained for any other specimen, with the exception of those which had the stiffeners attached by continuous fillet welds, that it was thought superfluous to test more than two specimens. The stiffeners of the remaining two specimens were again cut with a saw and the stiffeners subsequently joined again with a butt weld which was reinforced with an angle strap of the form and dimensions shown in Fig. 16. These specimens are called G1 and G2. G1, however, differed somewhat from G2. When G1 was tested it failed after a small number of cycles. The ends of the angle reinforcement, where the fatigue failure started and which had been left proud in specimen G1 were, therefore, ground away for specimen G2, together with part of the fillet weld at this point, in order to create a smooth transition between the strap and the angle stiffener.

Specimens Code Letter K. The tests with specimens F, G1 and G2 were merely exploratory, but they showed that some other type of strap would have to be designed if results were to be obtained approaching those obtained with the plain butt weld. Mr. A. T. S. Gardiner, one of the author's collaborators, suggested a strap, illustrated in Fig. 17, in which the end of the strap is placed near the neutral axis. This type of reinforcement is called the "Gardiner" strap in this report.

Fig. 9. Butt weld in stiffeners. Reinforcement ground off. View on outside of angle.

Fig. 10. Butt weld in stiffener. Reinforcement ground off. View on inside of angle.

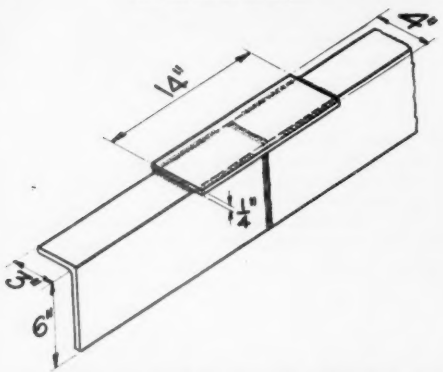


Fig. 11. Dimensions of Rectangular reinforcing strap specimens type "D."

Fig.12. Fillet welds on underside of rectangular strap showing gap in the way of butt weld.

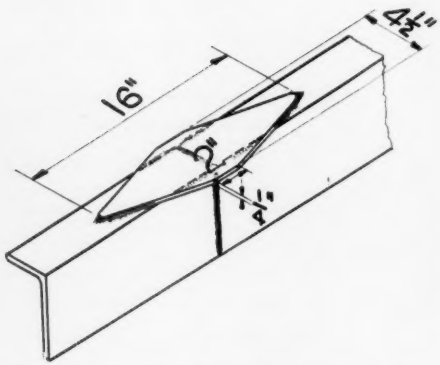


Fig. 13. Dimensions of diamond-shaped reinforcing strap specimens type "E."

Fig. 14. Fillet welds on underside of diamond-shaped strap showing gap in the way of butt weld.

The first specimen of this type was made from specimen F after this had fractured. The broken pieces of the rectangular strap were chiselled off, the saw cut was joined with a butt weld and the strap cut from an angle was then welded with fillet welds all round on to the angle stiffener. The fillet welds were not machined. This specimen was called K1.

After this specimen had been tested the result was sufficiently encouraging for four further similar specimens to be made from virgin material. Two of these specimens, K21 and K22, had straps of the dimensions shown in Fig. 17 and the dimensions of specimens K31 and K32 are shown in Fig. 18. Whilst the straps were actually cut from angles they could be made more quickly from flanged plate. The strap used in specimens K21 and K22 can be made by flanging a 45 deg. isosceles triangle and cutting off one corner and the strap used in specimens K31 and K32 can be made from a 30 deg. isosceles triangle.

Specimens C11, C12, C21 to C24, C31 and C32. The original programme envisaged the testing of four machined butt welded specimens called C1, C2, C3 and C4. This was subsequently extended by testing two additional specimens C11 and C12 with butt welds similar to those of C1 to C4, but with the reinforcement of the butt weld not removed. Six further specimens were made by using a hydrogen controlled electrode for making the butt welds and the butt welds were actually made with a slightly differing procedure, as explained previously. Of these six specimens, four were tested with the butt welds machined. These were specimens C21 to C24. The remaining two specimens C31 and C32 were tested with the butt welds not machined.

Specimens D21 to D24, and E21 to E24. After the specimens D1 to D4 and E1 to E4 had been tested at a stress range of either ± 8 tons per sq. in. or ± 6 tons per sq. in., four further specimens of each type and identical with D1 to D4 and E1 to E4 respectively, were tested under somewhat different stress conditions. These specimens are designated D21 to D24, and E21 to E24 respectively.

Specimens D1 to D4 and E1 to E4 were tested so that the stress range of ± 8 tons per sq. in. or ± 6 tons per sq. in. respectively was obtained at the point of transition between stiffener and strap, that is at the point of maximum stress concentration. The two series of specimens D21 to D24, and E21 to E24 were tested so that the stress range at some arbitrarily chosen point at some distance away from the strap along the stiffener was equal to the stress range obtained at the identical point in the specimens with continuous unjointed stiffeners, when these were tested at a stress range of ± 8 tons per sq. in. and ± 6 tons per sq. in. in the centre of the specimen at the point of maximum stress. The stress distribution as measured in specimen D3 exhibiting the stress concentration is shown in Fig. 19.

Specimens Code Letters H and I. Four specimens with continuous stiffeners were tested in which the stiffeners were attached by intermittent chain fillet welds as shown in Fig. 8b. Two of these specimens, H1 and H2, had scalloped stiffeners with scallops of the form and dimension shown in Fig. 20. The other two specimens I1 and I2 had continuous stiffeners without scallops.

Specimens Code Letter L. After a fairly large number of the tests had been completed it was decided to test a number of specimens fabricated in shipyards with joints such as are current practice. Four specimens called L1 to L4 were made with stiffeners butt welded and reinforced by an angle strap fillet welded to the stiffener on the inside as shown in Fig. 21. The holes in the vertical legs of the angles are erection holes to facilitate fitting *in situ* of the bosom bar preparatory to welding. The butt welds for specimens L1 and L2 were welded in the natural V-position whilst in specimens L3 and

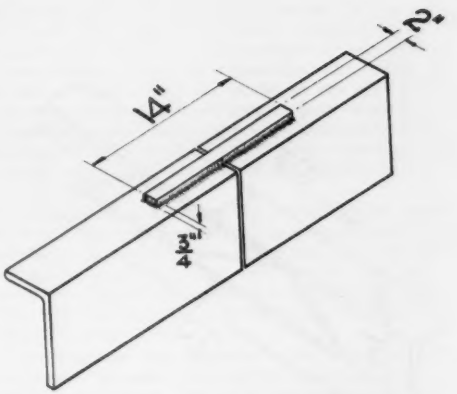


Fig. 15. Strap for unjointed stiffeners, specimen type "F."

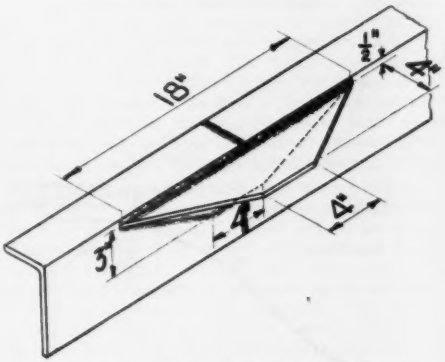


Fig. 16. Dimensions of angle strap specimens, type "G."

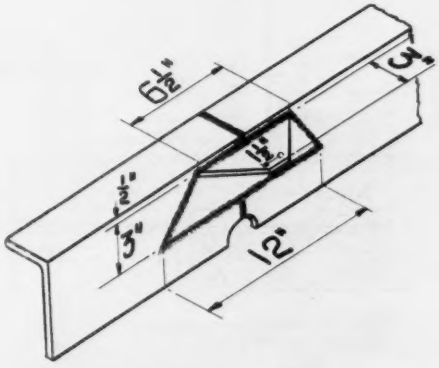


Fig. 17. Dimensions of Gardiner strap specimens, type "K21" and "K22."

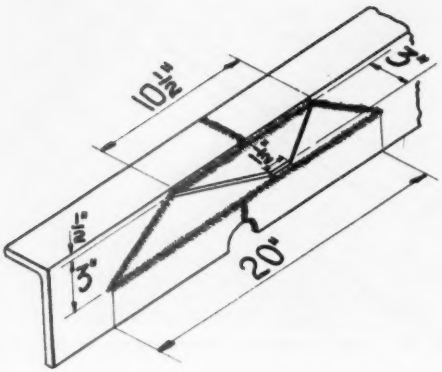


Fig. 18. Dimensions of Gardiner strap specimens, type "K31" and "K32."

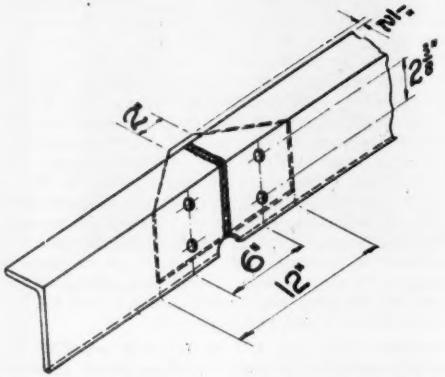


Fig. 21. Dimensions and form of strap for specimens L1 to L4.

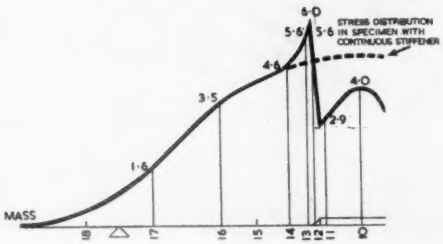


Fig. 19. Stress distribution in specimen "D3."

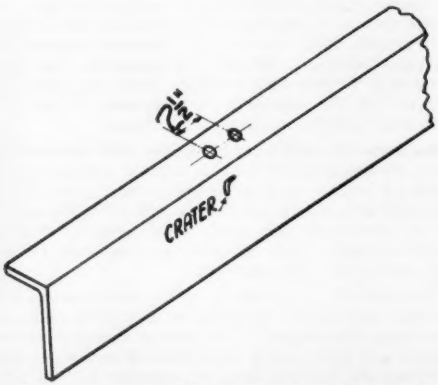


Fig. 22. Perforated stiffeners of specimens M1 and M2.

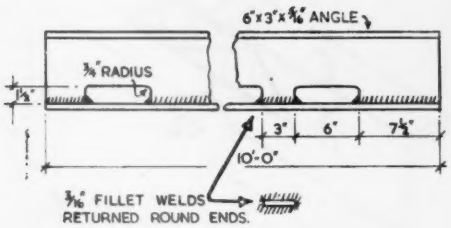


Fig. 20. Dimensions and spacings of scallops in stiffeners of specimen type "H."

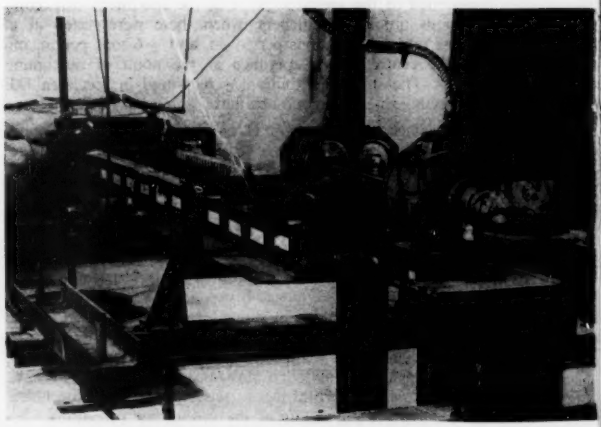


Fig. 23a. Specimen set up for test.

L4 the butt weld and strap were both welded in the overhead position. The stiffeners were welded to the plating in the downhand position in both cases.

Specimens Code Letters O and P. Seven specimens, O1, O2, O3 and P1, P2, P3 and P4 were similar to the specimens C11 and C12, that is, the stiffeners were joined with butt welds, the reinforcement being left on. Specimens of type O were made in one shipyard and specimens of type P in another.

In specimen O1 the back of the butt weld was chipped out and rewelded. Specimen O2 was also welded from both sides but slag was not removed. This specimen would contain a poor quality butt weld in comparison with specimen O1. Specimen O3 was also welded from both sides but only the slag was removed prior to welding from the back, the weld itself not being chipped out. This specimen should, therefore, be of intermediate quality between O1 and O2.

The two specimens P1 and P2 were intended to represent good shipyard practice, whilst in the specimens P3 and P4 it was tried to incorporate in the butt weld the most common fault, namely, some lack of fusion, particularly at the heel of the angle. The intermittent welding of the stiffeners to the plating was done downhand. For a distance of 18 in. on both sides of the butt weld the stiffeners were left unwelded until the butt was completed. When welding the butts the welder stood underneath the specimens and the butt was welded in the following sequence:

1. Top side of the horizontal flange: downhand.
2. Inside of the vertical flange: vertical.
3. Outside of the vertical flange: vertical.
4. Bottom side of the horizontal flange: overhead.

Specimens H11 to H14. It was believed that the cracks which were observed in specimens H1 and H2 at 45 deg. to the neutral axis, starting from the curved edge of the scallop, might be due to the fact that the flame cutting started hair cracks at these edges which propagated under fatigue loading or that the material round these edges was decarbonised and softened.

Since scallops are not generally flame cut in shipyards but punched, it was decided to have four further specimens H11 to H14 made in a shipyard with scalloped stiffeners identical to those in H1 and H2 but with the difference that the scallops in these stiffeners were punched.

Specimens Code Letter M. Finally, in order to determine the effect of holes on the fatigue strength of unjointed stiffeners, two specimens were made, each having two holes 13/16 in. diameter, at 2½ in. centres in the centre of the flange of the stiffeners, as is shown in Fig. 22. These two specimens are called M1 and M2.

Riveted Specimens Code Letter N. Four riveted specimens N1 to N4 were also tested. These had continuous unjoined 6 in. by 3 in. channel stiffeners riveted to the plating. Four riveted specimens with cut stiffeners joined by a riveted angle strap (¾ in. diameter: rivets at 7 diameters pitch) were also available, but these could not be tested by the resonance method for reasons which will be explained further on in this report.

TESTING PROCEDURE

All specimens were tested as beams in bending by the resonance vibration method which has been described in detail in a previous report.*

With this testing method the specimen forms the spring in a mass spring system which is excited near its natural frequency. The system is excited by a mechanical out-of-balance exciter which consists essentially of two unbalanced masses rotating in opposite directions. The testing force proper is derived from the inertia of the specimen and vibrating masses; the out-of-balance force applied to the specimen is small in comparison with the inertia force of the system and only serves to maintain the vibration which, without continuous excitation, would rapidly die out in consequence of damping.

In the present series of tests the vibration exciter was not, as it was in the previous tests on H-beams, attached in the middle of the specimen. In order to keep the centre of the specimens, where the joints were located, free from all attachments, the exciter was attached at one end. A balancing mass was attached to the specimen at the other end for the sake of symmetry.

The specimens were supported at the nodal points. The position of the nodal points and the natural frequency were found by calculation. The actual natural frequency of the specimen was 4,300 cycles per minute and this agreed very closely with the calculated natural frequency. All tests were carried out slightly below this frequency and approximately four hours were required to run up one million loading cycles.

The calculated position of the nodal points, approximately 18 in. from the ends of the specimen, were very close to the actual nodes. Each specimen was supported in two frames placed at the nodal points. The frames were carried in bearings which were bolted to the floor. The trunnions of the frames were arranged at the level of the neutral axis of the specimen so that the frames were free to pivot without imposing any restraint when the specimen executed bending vibrations. A specimen set up for testing is shown in Fig. 23.

Extensive strain measurements were carried out for one pilot specimen with electric resistance strain gauges and a cathode ray oscillograph. The state of stress in the specimen and the corresponding deflections were determined for three different testing speeds, all very near 4,300 r.p.m., which gave maximum deflections at the centre of the specimen of 0·1 in., 0·115 in. and 0·15 in. respectively. The deflection was measured relative to the nodes and is, therefore, the deflection of the length of the specimen between the nodes, that is, over approximately 7 ft. In order to obtain the deflection over the entire 10 ft. length, the deflection at the

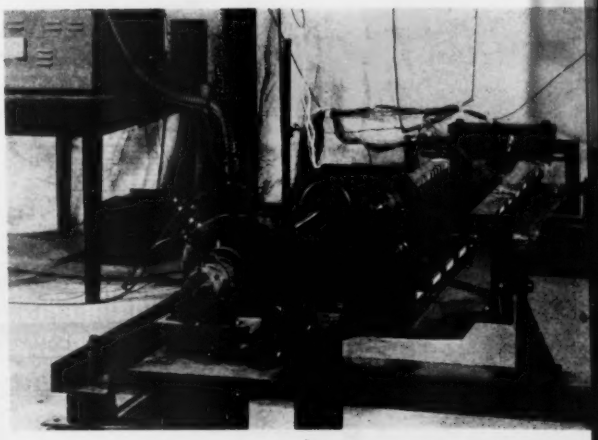


Fig. 23b. Specimen set up for test.

* A. L. Percival and R. Weck. "Fatigue Tests by the Resonance Vibration Method on Four Welded H-Beams." First interim report, FE.8 Committee on the Behaviour of Welded Structures under Dynamic Loading, British Welding Research Association, January, 1947.

free ends must be added since these ends deflect upwards when the centre of the specimen deflects downwards.

In consequence of the fact that the loading of the specimen is due to its own inertia, the resulting state of stress is rather complex. The loading is distributed over the whole of the specimen and the load at any point is equal to the element of mass at that point multiplied by the amplitude of vibration at that point and the square of the circular frequency. Since the amplitude is practically constant for all points at any cross section and the square of the frequency is constant for all cross sections, the loading at any cross section is distributed approximately as shown in Figs. 24a and 24b. If Fig. 24a represents the loading at a cross section near the centre of the specimen where the deflection is a maximum, the loading at any cross section nearer the ends is smaller because the amplitude of vibration there is smaller than at the centre. Consideration of the loading at any cross section shows that when the whole specimen, considered as a beam spanning between the nodes, deflects downwards, the plate, considered as spanning between the two stiffeners, must deflect upward in the centre. Because of this transverse bending of the plate in addition to the longitudinal bending, the stresses in the plate must be bi-axial, as they would be, in fact, if the plate were part of a ship's hull subjected to water pressure.

The stress distribution at the central cross section, obtained from strain measurements with electric resistance strain gauges attached at those points where numerical values for the stresses are shown in the diagrams, are plotted in Figs. 25 to 30 for three different testing speeds producing central amplitudes of 0·1 in., 0·115 in. and 0·15 in. respectively. It will be observed from these diagrams that the maximum longitudinal bending stress occurs at the heel of the angle and falls off rapidly from there towards the toe. The distribution of bending stress in the vertical leg of the angle is linear as expected and the point of zero stress coincides approximately with the calculated neutral axis of the cross section. Each of the numerical values given in the diagrams has been obtained from strain measurements in the longitudinal and transverse direction of the specimen. That is, at each point marked, two strain gauges were attached to the specimen, one in the direction of the axis of the specimen and one at right angles to the axis. The longitudinal and transverse stresses which are plotted in the diagrams were calculated from the strain measurements on the assumption that these are the directions of principal stresses, and that the state of stress is bi-axial.

The distribution of longitudinal stress in the plate is not quite uniform. On the inside surface (surface A) the stress is actually larger at the centre of the specimen than at the edges, and on the outside surface (surface B) the stress is larger at the edges than at the centre. This is rather paradoxical considering that the inside surface of the plate is, of course, nearer to the neutral axis than the outside surface, so that one would expect the stress at the outside surface to be slightly larger than the stress at the inside surface. The reason for this apparent paradox must be seen in a longitudinal bending moment acting in the plate alone and which is superimposed on the bending moment of the specimen as a whole. Consider the instant when the specimen has reached its maximum upward deflection, when the stress

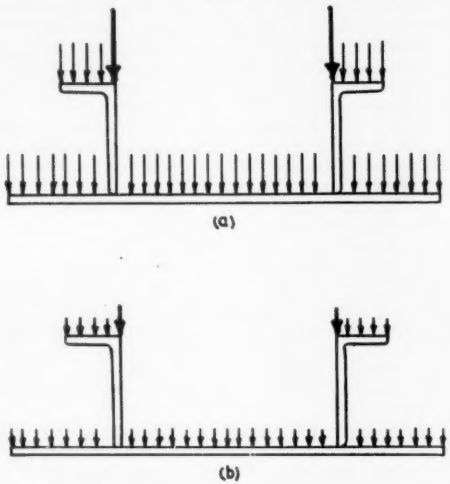


Fig. 24. Distribution of load in (*a*) central and (*b*) nodal cross-section.

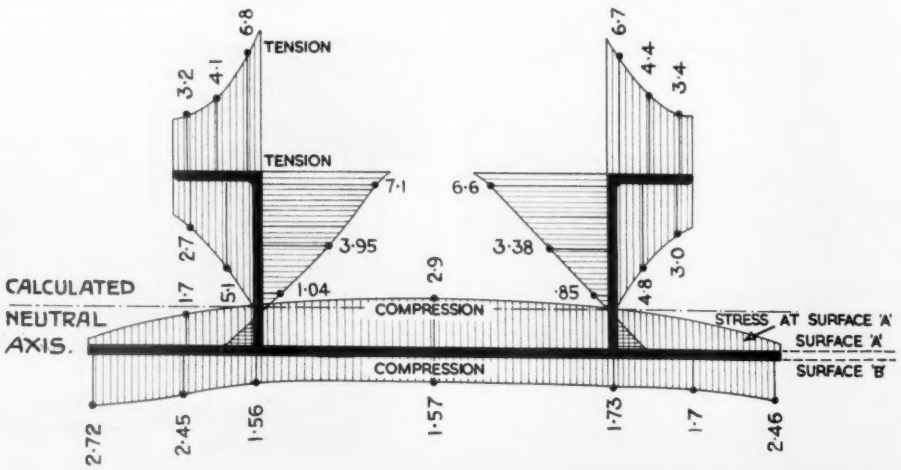


Fig. 25. Distribution of longitudinal stress (tons per sq. in.) at central cross-section for 0·1 in. central amplitude.

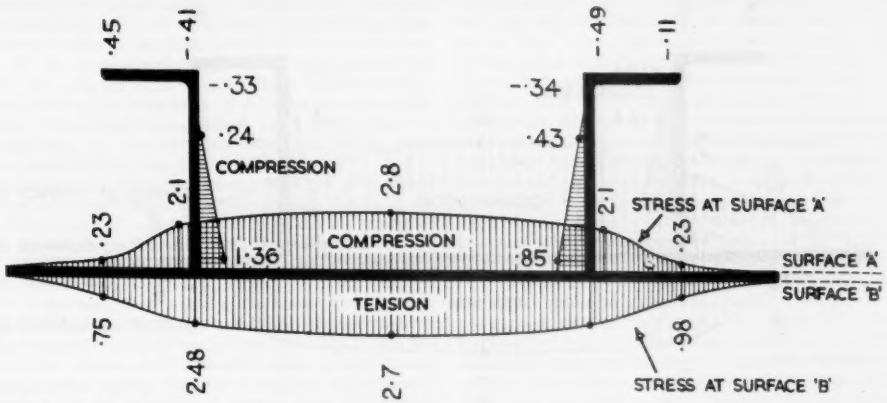


Fig. 26. Distribution of transverse stress (tons per sq. in.) at central cross-section for 0·1 in. central amplitude.

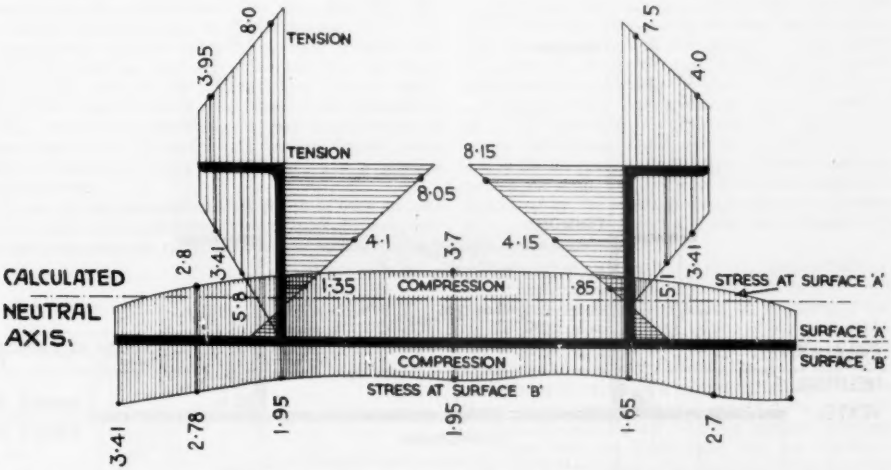


Fig. 27. Distribution of longitudinal stress (tons per sq. in.) at central cross-section for 0·115 in. central amplitude.

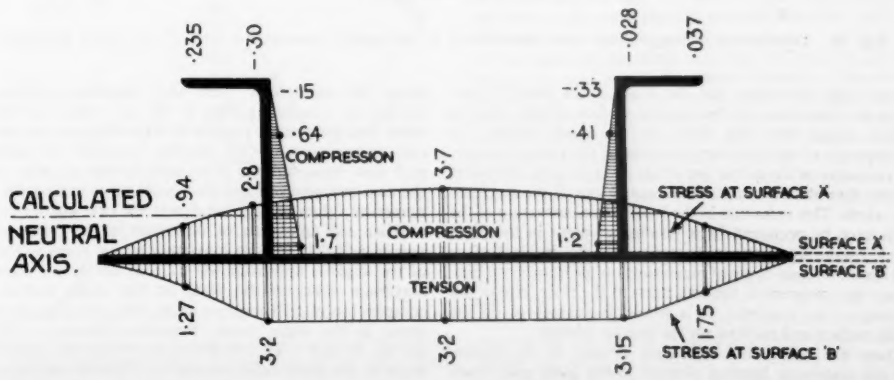


Fig. 28. Distribution of transverse stress (tons per sq. in.) at central cross-section for 0·115 in. central amplitude.

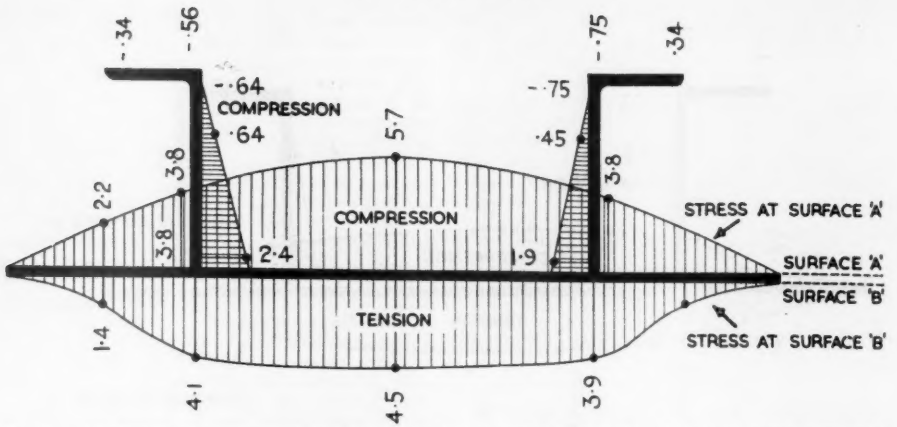


Fig. 29. Distribution of transverse stress (tons per sq. in.) at central cross-section for 0·15 in. central amplitude.

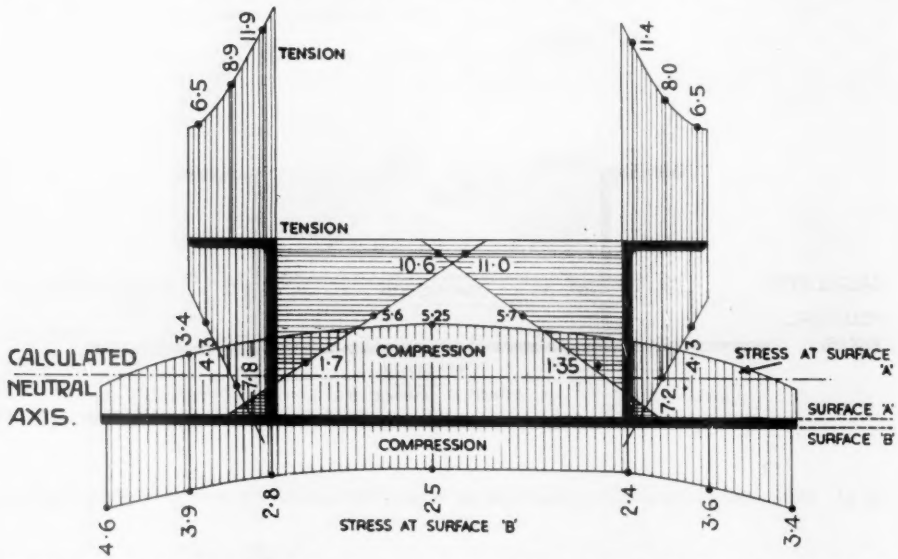


Fig. 30. Distribution of longitudinal stress (tons per sq. in.) at central cross-section for 0·15 in. central amplitude.

in the angles is tension and the stress in the plate is compression. The stress on the outside surface should then be slightly larger than the stress on the inside surface. In consequence of the transverse bending of the plate, however, the curvature of the centre line of the plate must be somewhat smaller than the curvature of the neutral axis of the specimen as a whole. This reduction in the longitudinal curvature of the plate must be produced by a bending moment in the plate which results in compressive stresses on the inside surface and tensile stresses of equal magnitude on the outside surface. Hence the compressive bending stress in the plate, due to the bending of the specimen, as a whole, is augmented on the inside surface and reduced on the outside surface.

There are only small transverse stresses in the angles, but the transverse bending stresses in the plate may reach values of sufficient magnitude to produce fatigue failure along the continuous fillet weld attaching stiffeners to plating. In considering Figs. 25 to 30, it must be borne in mind that the stresses plotted in these diagrams are reached only momentarily at the extreme amplitude of deflection and that these stresses completely revert to zero during the next quarter cycle and then build up to exactly the same numerical values of opposite sign in the next quarter cycle.

When the amplitude of deflection in the centre of the specimen is 0·15 in., the maximum tensile stress at the heel of the angle is approximately 12 tons per sq.in., whilst the maximum stress in the plate on the inside surface is a compression of 5·25 tons per sq.in. (Fig. 30). The maximum stress in the angle varies, therefore, between +12 tons per sq. in. and −12 tons per sq.in., whilst the longitudinal stress in the plate varies between −5·25 tons per sq.in. and +5·25 tons per sq.in. The transverse stress which is a

maximum on the inside surface of the plate is 5·7 tons per sq.in. compression (Fig. 29) at the instant when the maximum longitudinal stress at the same point is 5·25 tons. per sq.in. (Fig. 30). On the outside of the plate, however, the transverse stress is 4·5 tons per sq.in. tension for a maximum longitudinal stress at the same point of 2·5 tons per sq.in. compression. The corresponding figures for a stress range of approximately ± 8 tons per sq.in. at the heel of the angle can be obtained from Figs. 27 and 28.

The longitudinal stress was measured at the point where it reaches its maximum for each cross section, that is, at the heel of the angle all along the specimen and the results of these measurements together with the deflections of the specimen are plotted in Fig. 31. From these diagrams it is evident that the maximum stress in the whole of the specimen occurs at the heel of the angle in the central cross section, and it is this stress value upon which all the fatigue data given in this report are based. It can be seen from Fig. 31 that the stress curves, which are of the same shape as the bending moment curves, since the modulus of section of the specimens is constant for the entire length, have a point of inflection at the nodes. The shear stress at these points is therefore a maximum, although there is, of course, no vertical reaction transmitted to the foundations other than that from the dead weight of the specimen. In considering Fig. 31, it must be remembered that the deflection is equal upwards and downwards from the neutral position and that the stress values at any point of the specimen vary between equal, positive and negative limits. The fatigue range determined in these tests is the alternating bending fatigue range as distinguished from the basic tensile bending fatigue range, which is obtained in tests between zero and a positive maximum stress.

The use of the resonance method for these tests involves a certain difficulty in establishing a sound basis of comparison between specimens with continuous or butt welded stiffeners on the one hand and specimens with stiffeners in which the butt joint was reinforced by a strap of one kind or another, on the other hand. The strap produces a local change in stiffness and a small change in mass. Both these changes will have a slight effect on the natural frequency, a more pronounced effect on the amplitude of vibration and a very considerable effect on the state of stress in the specimen. It would obviously be incorrect to base the comparison between a specimen with continuous stiffeners and a specimen with strapped stiffeners on equal stress range at the centre of the specimen. It is obvious that a much higher load would be required to produce a certain stress at the centre of the strapped specimen than at the centre of an unstrapped specimen. The two tests would, therefore, be carried out at very different loads and comparison of the number of cycles to failure would be misleading. A more rational basis of comparison can be established by testing the strapped specimen so that the stress range produced at the point of maximum stress concentration is the same as that in the centre of the specimen with continuous stiffeners. The test load, as is discussed in more detail in the Appendix, will then be somewhat smaller for the strapped specimens than it is for the continuous specimens.

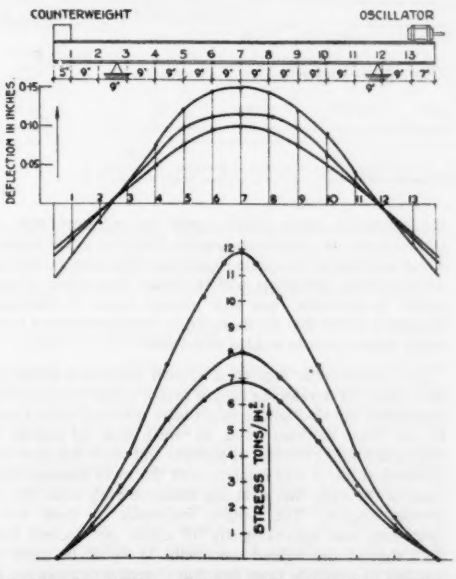


Fig. 31. Amplitudes and stresses along test piece (*maximum stress values (at corner of angle) shown for each cross-section.*)

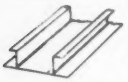
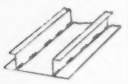
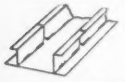
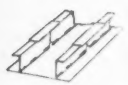
A third possibility is to take some arbitrary point along the stiffener at some distance from the strap and to carry out all tests at a stress range at this particular point of the same magnitude as the stress range at the identical point in a specimen with continuous stiffeners when tested at a range of maximum stress in the middle of, say, ± 8 tons per sq.in. or ± 6 tons per sq.in. It is explained in the Appendix that the curves for the stress distribution in the continuous specimen and in the strapped specimen will not perfectly coincide, even outside the strap. The difference will be only slight, however, and therefore, the inertia loading for the two specimens, one with continuous stiffeners and one with strapped stiffeners, will be almost identical.

The tests with the specimens having diamond shaped straps and rectangular straps were carried out in both ways. One set of four specimens was tested by maintaining the stress at the point of stress concentration at the same value as the maximum stress in the continuous specimens. Another four specimens were tested by keeping the stress at a point 16 in. away from the centre at a value equal to that measured at a point 16 in. away from the centre in the specimen with continuous stiffeners. All the other strapped specimens such as those with the angle strap and the Gardiner strap (specimens G and K) and the specimens which were fabricated in the shipyard (specimens L and M) were tested by maintaining a definite constant stress range 16 in. away from the centre of the specimen, this stress range being equal to that obtaining at the same place in the specimen with continuous stiffeners.

It is important in fatigue tests that the stress range should remain constant during the entire duration of the test and that the test should stop immediately after the crack has developed. The amplitude control device, described in detail in the first interim report (*cf.* p. 227*r*) was used to maintain constant amplitude and hence constant stress range and has proved entirely satisfactory. This amplitude control device also serves to stop the test as soon as a fatigue crack develops.

As soon as a crack develops the natural frequency of the specimen changes. This means that the motor speed will be nearer to or further away from the new natural frequency and hence the amplitude of vibration will be either larger or smaller than the amplitude of vibration prior to the development of the crack. The amplitude control device will try to restore the original amplitude by speeding up or slowing down the motor. The total range of speed variation permitted

Table 1

Type of Specimen	Specimen No.	Stress Range Tons/sq. in.	Number of Cycles to Failure	Location to Failure	Remarks
Continuous stiffener continuous fillets 	A1	±8 ±9	11,601,740 * 1,136,360	Along undercut of continued fillet weld	Failure after further 1,136,350 cycles at ±9 tons/in.²
	A2	±8	6,508,000	Ditto	
	A3	±7 ±8	17,254,000 * 11,254,000	Ditto	Failure after further 11,254,300 cycles at ±8 tons/in²
Continuous stiffener intermittent staggered fillets 	B1	±8	3,835,340	Transverse cracks starting from end of intermittent fillet welds at approx. 12 in. distance from centre	
	B2	±8	4,717,940		
Stiffeners with butt-welds machined ordinary electrode 	C1	±8	584,180	Through centre of butt weld starting from weld flaw at heel of angle	
	C2	±8	902,500		
	C3	±7	2,941,200		
	C4	±6	1,707,520		
Buttwelds unmachined ordinary electrode	C11	±8	573,000	Through centre of butt weld	
	C12	±8	1,034,620		
Buttwelds machined hydrogen controlled electrode	C21	±8	1,495,560	Outside butt weld	
	C22	±8	691,240	Through stray flash 10 in. away from weld	
	C23	±8	1,567,580 + 980,840	Through angle near weld	Specimen C23 failed in the stiffener after 1,567,580 cycles, was repaired and endured another 980,840 cycles when it failed near the butt weld
	C24	±8	1,056,180	Failure in plate near scallop	
Buttwelds unmachined hydrogen controlled electrode	C31	±8	1,118,560	Along undercut of butt weld	
	C32	±8	2,734,140	At end of transverse sealing run	
Stiffeners with butt-welds reinforced by rectangular strap 	D1	±8†	389,760	At end of fillet weld connecting strap	
	D2	±8†	470,000		
	D3	±6†	3,740,780 ** + 2,953,380	At edge of strap	Further 2,953,380 cycles for crack to travel full width of stiffener
	D4	±6†	7,620,140	Ditto	Fracture in both stiffeners
	D11	±8††	379,340	At end of fillet weld connecting strap	
	D12	±8††	155,280		
	D13	±6††	338,320		
	D14	±6††	777,800		

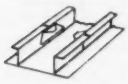
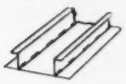
* Unbroken.
** Crack detected.
† Actual stress measured at point of stress concentration.
†† Nominal stress of continuous specimen, comparison established at point outside strap.

by the amplitude control device is, however, much smaller than that which would be required to restore the original amplitude of the uncracked specimen. Any change in motor speed more than 5 per cent. either way will automatically shut the whole testing plant down. Usually at the end of a test the motor switches itself off even before the crack is visible to the naked eye and usually several thousand further cycles are required to make the crack visible; that is, in order to make the crack visible the plant has to be started up again for a very short time and the speed of the motor has to be continuously changed to follow the natural frequency of the specimen which keeps changing as the crack propagates.

A number of specimens were made in which the stiffeners were channels riveted to the plating; the channels were cut in the centre of the specimen and a joint was made by means of a riveted angle strap. When the first of these specimens was tested, it was found that the riveted strap absorbed so much energy—this becomes evident by the very rapid heating up of the strap and the rivets—that the amplitude of vibration and consequently the stress range which could be produced with the available power, was not large enough, that is, the maximum stress which could be produced with the available motor was much smaller than the stress range at which the tests of the welded specimens had been carried out. These riveted specimens will be tested later when a larger motor is available, but this interim result is interesting because it shows that the damping in riveted structures is very much higher than in welded structures.

It is conceivable that these riveted specimens would not have failed by developing fatigue cracks similar to the welded specimens, but that failure might have occurred fairly rapidly by the rivets working loose, in which case, of course, the structure would have lost its stiffness and could not have been vibrated at all. It was evident from the rapid heating taking place in the strap that rivet slip occurred even under the low stresses applied. The natural frequency of these riveted specimens was approximately 15 cycles per second lower than that of the welded specimens. It would be quite unjustified to conclude from this that riveted structures are less liable to fatigue failure than welded structures. Such experimental evidence on the fatigue strength of riveted structures as there is, indicates that the fatigue strength of riveted

Table 2

Type of Specimen	Specimen No.	Stress Range Tons/sq. in.	Number of Cycles to Failure	Location of Failure	Remarks
Stiffeners with butt-welds reinforced by diamond shaped strap	E1	±8†	850,460	At end of fillet weld connecting strap	
	E2	±8†	669,780		
	E3	±6†	19,982,300	At point where edge of strap crosses edge of flange	
	E4	±6† ±7	29,202,840 * + 6,333,480		
	E11	±8††	2,108,100	At end of fillet and at cross-over point	
	E12	±8††	2,214,920	At end of fillet in one stiffener at cross-over point in other stiffener	
	E13	±6††	18,132,680	In plate and stiffener starting from intermittent fillet weld	
	E14	±6††	4,454,440	Centre of strap and flange	
Stiffeners without butt-welds, gap spanned by strap	F	±8 (at centre of strap)	46,620 (beginning of crack) 145,880 (fracture through strap complete)	Centre of strap	
Stiffeners with butt-welds reinforced by tapered angle straps	G1	±6† ±8†	87,280	End of strap	
	G2	±8†	270,240	Ditto	
Stiffeners with butt-welds reinforced by Gardiner straps 	K1	±8††	757,110	Along undercut of fillet weld connecting strap	
	K11	±8††	408,460		
	K12	±8††	882,180	Ditto	
	K21	±8††	687,380		
	K22	±8††	1,384,740		
Continuous stiffeners intermittent chain weld 	I1	±8	1,195,540	Along undercut of intermittent fillet welds	
	I2	±8	2,793,400	Ditto	

* Unbroken.
† Actual stress measured at point of stress concentration
†† Nominal stress of continuous specimen, comparison established at point outside strap.

joints is not higher than that of welded joints and may be inferior to that of butt welded joints. When this report was prepared, the author received detailed information from America of 98 fatigue failures in American riveted bridges.*

DISCUSSION OF RESULTS

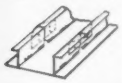
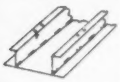
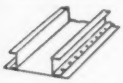
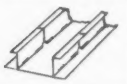
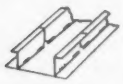
Altogether 66 specimens were tested, of which 21 had been made in shipyards, including the 4 riveted specimens. The test results are summarised in Tables 1 to 3. A summary of averages is given in Table 4. When these test results are examined it will be observed that sometimes a considerable difference has been obtained in the number of cycles to failure for similar specimens tested at the same stress range. In some cases a shorter life has been obtained for a specimen tested at a lower stress range than for a similar specimen tested at a higher stress range as, for instance, in the case of C3 and C4. Both these phenomena are not unusual in fatigue tests and it is obvious that they make interpretation of the test results somewhat difficult if only a small number of specimens of each type is tested. Nevertheless, a number of interesting and important facts have emerged quite clearly in this investigation.

It is well known that when the results of fatigue tests with many identical specimens tested at different stress levels are plotted as number of cycles to failure versus stress, a curve of the type shown in Fig. 32 is obtained, called a S-N curve. The curve approaches a line parallel to the number-of-cycles axis asymptotically and the stress level at which this line can be drawn is the endurance limit of the specimen. The form of the S-N curve shows that in the region of long life a comparatively small change in the test stress must be accompanied by a large change in the number of cycles.

To illustrate this, let us assume that the life of some component when tested at ±8 tons per sq.in. is $n = 2{,}000{,}000$ cycles. In order to find the stress, S, at which the component

* Report of Committee 15—Iron and Steel Structures—of the American Railway Engineering Association. Bulletin 485, January, 1950, page 470. Progress Report, "Stress Distribution in Bridge Frames—Floor Beam Hangars."

Table 3

Type of Specimen	Specimen No.	Stress[1] Range Tons/sq. in.	Number of Cycles to Failure	Location of Failure	Remarks
Continuous scalloped stiffeners chainwelded	H1	±8	1,451,050	Numerous cracks resulting in almost complete disintegration of specimens	
	H2	±8	1,568,760	Ditto	
Continuous scalloped chainwelded scallops punched			**SPECIMENS MADE IN SHIPYARDS**		
	H11	±8	1,161,590		
	H12	±8	1,138,680	Along undercut of fillet welds and at toe of return fillets	
	H13	±8	1,324,560		
	H14	±8	973,380	Broke in angle as well	
Butt weld and strap 	L1	±8††	242,540		
	L2	±8††	313,220	At end of strap through toe of fillet weld and also in the buttweld of L_1	
	L3	±8††	378,140		
	L4	±8††	617,900		
Continuous stiffeners with two holes 	M1	±8††	513,080	Through crater and hole	
	M2	±8††	401,900	Through hole	
Continuous riveted channel stiffeners 	N1	±8	2,611,900	Failed in badly corroded channel	
	N2	±8	19,914,760 *	Fracture in channel	Specimen N4 repaired by welding up crack. After 709,060 cycles failure in same place
	N2	±9	1,035,500	Ditto	
	N3	±8	25,303,860 *	Ditto	
	N3	±8·5	1,486,680	Ditto	
	N4	±8·5	1,974,920	Fracture under supporting frame in consequence of fretting	
	N4	±8·5	709,060		
Butt welds made in Shipyard "X." Reinforcement left on. 	O1	±8	1,747,800		
	O2	±8	906,320	Through butt weld in all cases	
	O3	±8	1,188,560		
Butt welds made in Shipyard "Y." Reinforcement left on. 	P1	±8	711,320	Failure along undercut of butt weld	
	P2	±8	439,000	Ditto	
	P3	±8	505,040	Ditto	
	P4	±8	341,840	Ditto	

* Unbroken.

†† Nominal stress of continuous specimen, comparison established at point outside strap.

will endure twice the number of cycles $N=2n$, we can use the empirical formula

$$F=S\left(\frac{N}{n}\right)^k$$

where F is the stress at which failure occurred for n cycles and k is an experimental constant. In the present example

$F=8$ tons per sq.in., $n=2\times10^6$ and $N=4\times10^6$.

The constant k may vary widely between $k=0{\cdot}1$ and $k=0{\cdot}4$ and must be determined experimentally since it depends on the geometry of the specimen. Let us assume $k=0{\cdot}1$. In this case we obtain

$$8=S\left(\frac{4{,}000{,}000}{2{,}000{,}000}\right)^{0{\cdot}1} \quad \text{and} \quad S=7{\cdot}46 \text{ tons per sq.in.}$$

This calculation shows that for $k=0{\cdot}1$ a decrease of a little more than 0·5 ton per sq.in. will virtually double the life from 2×10^6 cycles to 4×10^6 cycles. It cannot be assumed, of course, that in the present series of tests the constant is $k=0{\cdot}1$, in fact, it is not possible to determine this constant from such few test results. It is important, however, to bear in mind when considering the test results given in Tables 1 to 4 that large differences in numbers of cycles to failure for different specimens represent comparatively small differences in fatigue strength.

Table 4

Averages of Test Results at ±8 tons per sq. in.

Type of Specimen	No. of Specimens Tested	No. of Specimens Averaged	Average Number of Cycles
Continuous Stiffeners			
A, Continuous fillets	3	3	9,787,910+
B, Staggered fillets	2	2	4,276,640
I, Chain fillets	2	2	1,994,470
H1H2, Scalloped, flame cut	2	2	1,509,900
H1IH14, Scalloped, punched	4	4	1,149,550
N, Riveted channel	4	2	22,609,310+
M, Perforated	2	2	457,490
Butt Welded			
C1C2, Machined	2	2	743,340
C1IC12, Unmachined	2	2	803,810
C2IC24, Hydrogen controlled electrode	4	3	1,700,050
C3IC32, Hydrogen controlled electrode, unmachined	2	2	1,926,350
O, Shipyard "X"	3	3	1,280,890
P1P2, Shipyard "Y"	2	2	575,160
P3P4, Shipyard "Y"	2	2	423,440
P1-P4, Shipyard "Y"	4	4	499,300
Strapped Butts			
D1D2, Rectangular strap	2	2	429,880
D1ID12, Rectangular strap	2	2	267,310
E1E2, Diamond strap	2	2	765,120
E1IE12, Diamond strap	2	2	2,161,510
K1IK12, Gardiner strap	2	2	645,320
K2IK22, Gardiner strap	2	2	1,036,060
L, Shipyard strap	4	4	387,950

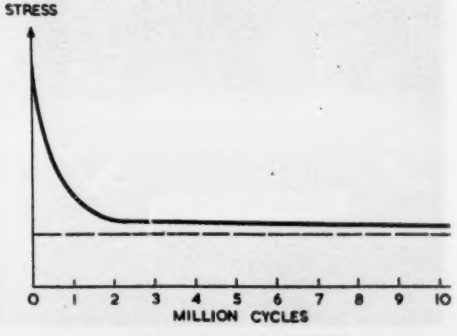


Fig. 32. Typical S—N curve.

Specimens without Joints in Stiffeners. Of the specimens without joints in the stiffeners, those of type A with continuous fillet welds are undoubtedly superior to any of the other welded specimens tested. Specimen A1 sustained 11,601,740 cycles at ±8 tons per sq.in. and failed after a further 1,136,360 cycles at ±9 tons per sq.in. Specimen A3 failed after 11,254,000 cycles at ±8 tons per sq.in. after having sustained already 17,254,000 cycles at the lower stress range of ±7 tons per sq.in. Specimen A2 failed after 6,508,000 cycles at ±8 tons per sq.in. This value is low in comparison with those obtained for specimens A1 and A3 and is an indication of the scatter of test results to be expected. Nevertheless, even this low value is much larger than the value obtained for any other of the welded specimens.

All three specimens of type A failed in the same manner, by developing fatigue cracks in the longitudinal direction of the specimen along the undercut of the fillet weld as shown in Fig. 33. These cracks are caused by the transverse bending stress in the plate.

The riveted specimens with continuous channel stiffeners, N2 and N3, lasted even longer. At a stress of ±8 tons per sq.in. specimen N2 sustained 19,914,760 cycles and failed after a further 1,035,500 cycles at a stress of ±9 tons per sq.in. Specimen N3 sustained 25,303,860 cycles at ±8 tons per sq. in. and failed after a further 1,486,680 cycles at ±8·5 tons per sq. in. In both these specimens fracture occurred at the point of maximum bending stress in the centre of one of the channel stiffeners. These two riveted specimens were undoubtedly better than the welded specimens of type A and the reason for the better behaviour must be seen in the absence of the stress concentrations caused by the longitudinal fillet welds. It is possible that in these riveted specimens fatigue cracks had started from the rivet holes before the fracture in the channels developed, but no such cracks could be discovered by visual inspection.

The other two riveted specimens, N1 and N4, had a very much shorter life. Specimen N1 failed after only 2,611,900 cycles at ±8 tons per sq.in. The cause of the premature failure was quite evident. One of the two channels was badly pitted by corrosion and it was this channel which failed first. The other specimen, N4, was tested at a stress of ±8·5 tons per sq.in. and failed after 1,974,920 cycles. The failure took place under one of the supporting frames where the specimen was held down and there was evidence of very severe fretting at this point. A similar failure had been experienced very early on when the prototype specimen which was used for the determination of the stress distribution at various stress levels had been tested. It is, of course, well known that severe fretting may give rise to premature fatigue failure. The specimen N4 was subsequently repaired by welding up the crack and was tested again at ±8·5 tons per sq.in., and it failed after a further 709,060 cycles at exactly the same spot. It must be borne in mind that these failures took place at a point where the stress is really quite low, approximately ±3 tons per sq.in.

One of the surprising results in this investigation was the marked superiority of the specimens welded with intermittent staggered fillet welds over those welded with intermittent chain fillet welds. Whilst the specimens B1 and B2 sustained 3,835,340 cycles and 4,717,940 cycles at ±8 tons per sq.in., the specimens welded with intermittent chain fillet welds, I1 and I2, at the same stress range of ±8 tons per sq.in. only sustained 1,195,540 and 2,793,400 cycles respectively. This gives an average life of 4,276,640 cycles for specimens of type B and 1,994,470 cycles for specimens of type I. Both types of specimens are, however, inferior to the specimens of type A. In the case of specimens type B, the failure started as a transverse crack in the plating, starting from one end of one of the intermittent fillet welds as shown in Fig. 34. In the

Fig. 33. Typical failure of specimen type A.

specimen shown, actually two cracks developed, one in the plating from one end of an intermittent fillet weld and the second crack going into the angle from the end of another intermittent fillet weld. It is to be noted that this type of crack never developed in the centre of the specimens where the longitudinal bending stress which causes them is largest, but at some distance away from the centre where the intermittent fillet welds would be subjected to direct stress and shear.

The failures in the specimens welded with intermittent chain fillet welds were entirely different. There the fatigue cracks developed along the undercut of the fillet welds as is shown in Fig. 35. These cracks were similar to those experienced in specimens of type A. It is difficult to account for this difference in behaviour of specimens type I and specimens type B. Specimens type B failed in consequence of the longitudinal bending stress, and it is conceivable that the concentration of fillet welds on both sides when chain welding is used as in specimens of type I produces such a severe change in stiffness in the transverse direction in comparison with the specimens of type B and such severe stress concentrations in comparison with specimens of type A, that failure takes place in these specimens in consequence of transverse bending, very much earlier than those of type B or type A.

When the stiffeners are scalloped the life is reduced even

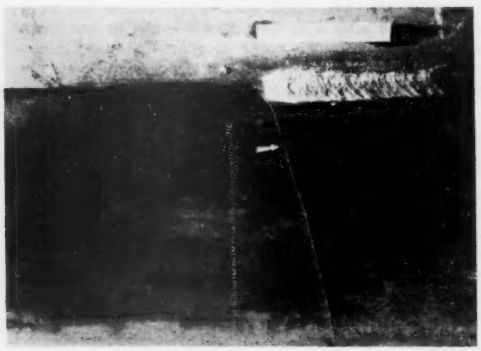


Fig. 34. Typical failure of specimen type B.

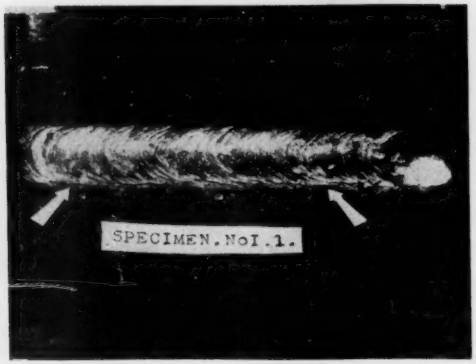


Fig. 35. Typical failure of specimen type I.

further. The two specimens H1 and H2 which had been made in the laboratory by flame cutting the scallops, and which were tested at ±8 tons per sq. in., failed after 1,451,050 cycles and 1,568,760 cycles respectively, giving an average of 1,509,905 cycles as compared with the average for the not scalloped specimens I1 and I2 of 1,994,470 cycles.

The mode of failure of these specimens H1 and H2 was very interesting. They developed so many cracks in different places that one could speak almost of complete disintegration. The cracks were of three types. One type of crack occurred along the undercut of the return fillet attaching the prongs of the stiffeners, and this type of crack is shown in Fig. 36. The second type of crack is similar to that experienced with the specimens type I and is shown in Fig. 37. This crack followed the undercut of the intermittent fillet weld. The third type of crack is shown in Figs. 38 and 39. It started in the circular part of the scallop and progressed approximately under 45 deg. towards the centre of the stiffener roughly in the direction of the principal stress. These cracks only occur, however, near the supports of the specimen, that is, at the points where the shear is a maximum, whilst the longitudinal bending stress is fairly small. At the points of maximum shear, however, the principal stresses at the neutral axis under 45 deg. to the axis of the specimen are a maximum in any case, even if there is no scallop. If there are scallops, stress concentrations will occur near the neutral axis under 45 deg. and these will give rise to this type of crack. Whether these cracks are to be expected in a ship

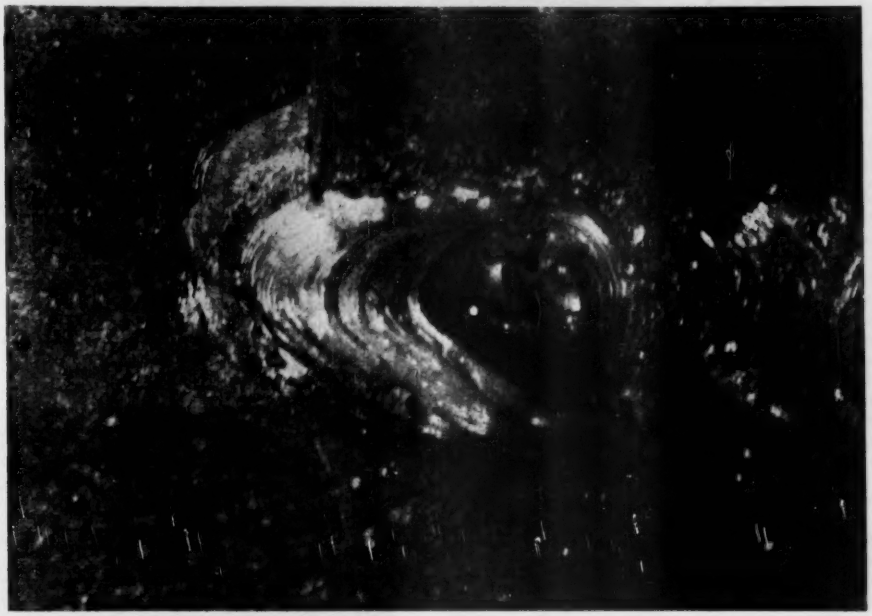


Fig. 36. Crack at return of fillet weld in specimen type H.

Fig. 37. Crack along undercut of fillet weld in specimen type H.

Fig. 38. Cracks through prongs in stiffener. Specimen type H.

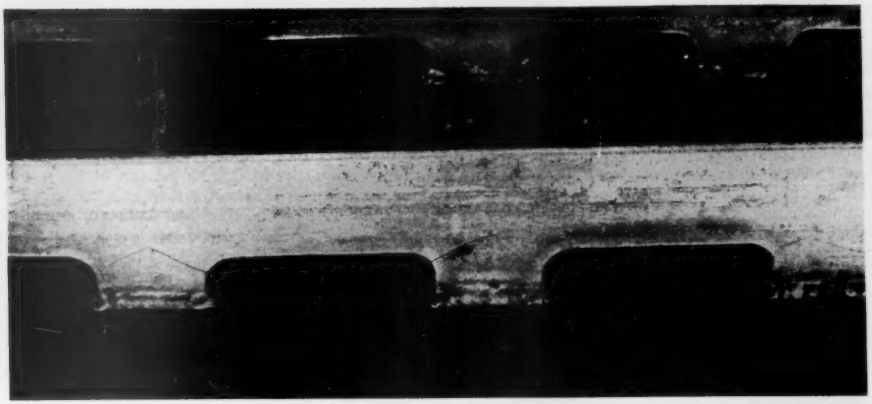


Fig. 39. Cracks through prongs in stiffener. Specimen type H.

depends on the position of the neutral axis in a large panel with many stiffeners and on the magnitude of the reactions at the ends of stiffeners.

Four specimens of exactly the same type, H11 to H14, were made in a shipyard by punching the stiffeners and when these specimens were tested none of them developed this particular type of crack. They failed by developing the type of crack shown in Fig. 36 and Fig. 37. The average life of these specimens, however, was only 1,149,552 cycles, which is somewhat less than the life of specimens H1 and H2, and is actually the lowest figure which has been found in any of the specimens without joints. The absence of the cracks under 45 deg. in these specimens is remarkable. This may be due to the work hardening of the punched edges, whilst the flame cut edges are presumably softened and decarburised and therefore offer less resistance to fatigue than punched edges.

From the results obtained with the scalloped stiffeners, it does not appear that, in its present form, this type of construction gives the highest fatigue strength, and it would undoubtedly be worth while to investigate the stress distribution in stiffeners made with scallops of different form in order to see whether there is a type of scallop which will give a more favourable stress distribution.

Apart from the scalloping, the return fillets round the ends, whatever other advantages they may have, are a disadvantage from the point of view of fatigue. It is a well known fact, which has also been observed in other investigations, that such return fillets are likely to lower the fatigue strength of the component if they are normal to the direction of the larger stress. One of the reasons for this may be that there is a tendency at such return fillets to pile on weld metal. The results might be better if it were practicable to make these return fillets continuously with the intermittent fillets proper without stopping and starting.

Stiffeners with Butt Welds. The first four specimens with machined butt welds, C1 to C4, failed after 584,180 and 902,500 cycles respectively at a stress of ± 8 tons per sq.in., after 2,941,200 cycles at ± 7 tons per sq. in. and after 1,707,520 cycles at ± 6 tons per sq.in. All these specimens failed through the centre of the butt weld, and the type of failure is shown in Fig. 40. When the reinforcement was left on as in specimens C11 and C12, the failure still went through the centre of the butt weld as is shown in Fig. 41. These two specimens, C11 and C12, lasted for 573,000 and 1,034,620 cycles respectively when tested at ± 8 tons per sq.in. This is an average of 803,810 cycles which, surprisingly, is even somewhat higher than that obtained for the specimens with machined butt welds which is 743,340 cycles.

Specimens C21 to C24 were welded with a hydrogen controlled electrode of which it was known that all weld metal specimens had given a fatigue strength at least 50 per cent. in excess of that normally to be expected from

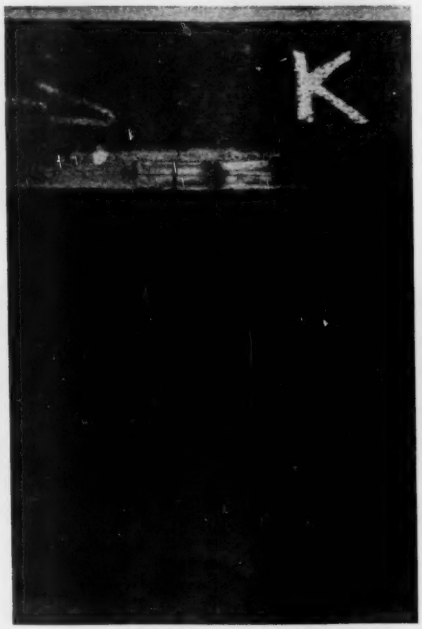


Fig. 40. Typical failure through centre of butt weld in specimen type C1 and C4.

Fig. 41. Typical failure through centre of unmachined butt weld. Specimens C11 and C12.

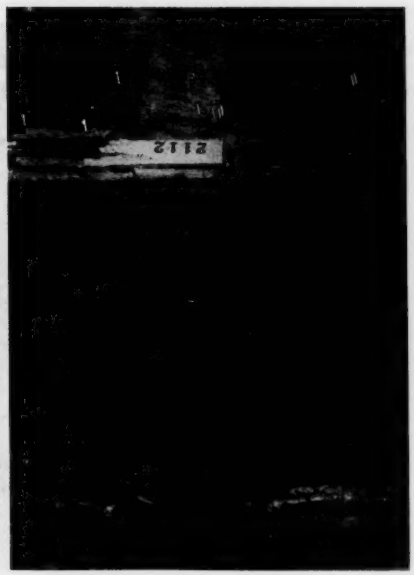


Fig. 42. Crack in specimen C21.

ordinary electrodes. All these specimens broke outside the butt weld. The failure of specimen C21, which was similar to that of specimen C23, occurred in the vicinity of the weld and is shown in Fig. 42. Specimen C21 failed after 1,495,560 cycles. Specimen C23 failed after 1,567,580 cycles in consequence of fretting similarly as specimen N4 had failed under one of the supporting frames. It was repaired and then a crack similar to that observed in specimen C21 was observed near the butt weld in addition to a second fracture under the supporting frame where the repair had been effected. Specimen C24 did not fail in the stiffener at all, but fractured along the undercut of the return fillet weld in way of the central scallop after 1,056,180 cycles. The location of this fracture is marked by arrows in Fig. 43. Specimen C22 failed through a stray flash after 691,240 cycles 10 in. away from the weld. This fracture is shown in Fig. 44 and Fig. 45 shows its position relative to the butt weld. If the result for specimen C22 is ignored, which is justified because the failure in this case was definitely due to the accidental flash, and if the total life of specimen C23 is reckoned from the time of starting the test until the fracture in the vicinity of the butt weld appeared, that is including the 980,840 cycles after repair, which is justified because the first failure was due to fretting, we obtain an average life for these specimens at a stress of ± 8 tons per sq.in. of 1,700,050 cycles which is considerably more than that obtained for specimens C1 to C4 with which these specimens can be compared.

Two specimens made in the same way as C21 to C24 with the reinforcement of the butt weld left on, lasted for 1,118,560 cycles and 2,734,140 cycles respectively at ± 8 tons per sq.in., which gives an average of 1,926,350 cycles. If this is compared with the average of 1,700,050 cycles for specimens C21 to C24, it appears that even with this electrode the removal of the reinforcement does not produce any improvement in the fatigue strength of the specimen. However, the number of tests are insufficient to establish this with certainty. The failure in these specimens C31 and C32 started on the inside of the angle from the end of the transverse sealing run of the butt weld in the angle as shown in Fig. 46. On the outside of the angle the fracture ran along the undercut of the butt weld as is shown in Fig. 47.

In most previous investigations on butt welds it has been shown that removal of the reinforcement increases the fatigue strength of butt welds. The present series of tests have not given the same results. In both series of tests C1 to C4, C11 and C12, and C21 to C27, the average number of cycles for the ground butt welds was smaller than that obtained for the butt welds with the reinforcement left on.

This may be due to one of two circumstances or both. In the first place the superiority of machined butt welds has been established for butt welds in plates and it is possible that the difficulties inherent in the butt welding of rolled sections always result in certain inevitable flaws being incorporated in the welds, and that machining only increases the fatigue strength of butt welds if they are inherently of very good quality. The other possibility is that the improvement cannot be realised by grinding as distinct from machining. It is known that grinding marks lower the fatigue strength of metal specimens and it is possible that any improvement that might have been realised by removing the reinforcement has been nullified by the effects of grinding.

The fact that none of the specimens C21 to C24 broke in the butt weld and two of them broke at some small distance from the butt welds, seems to suggest that the heating cycle in consequence of welding to which the material at some distance from the weld is subjected has some effect on the parent metal at this distance, weakening it under fatigue conditions. Other investigators also have found that butt

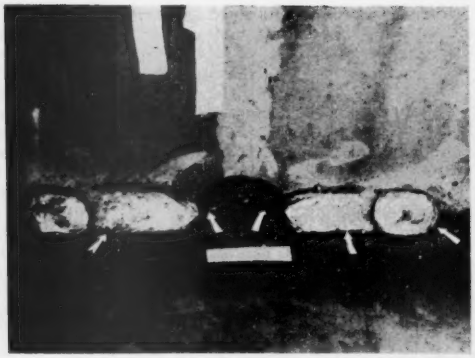


Fig. 43. Crack in specimen C24.

Fig. 44. Crack in specimen C22.

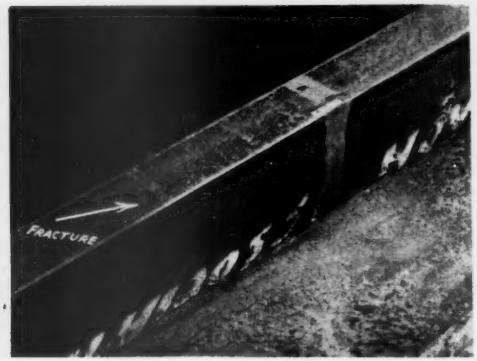


Fig. 45. Position of crack in specimen C22 relative to butt weld.

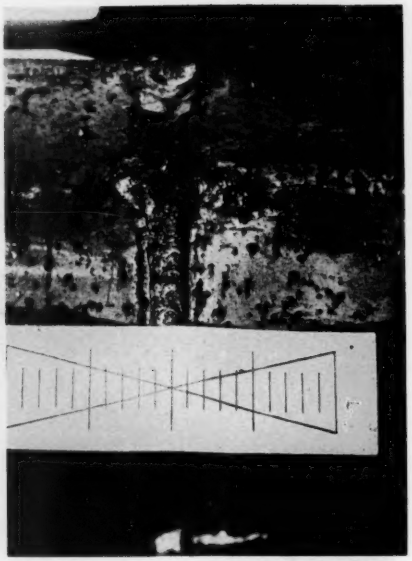


Fig. 46. Start of failure in specimen C31 at the end of the transverse sealing run on the inside of the angle.

Fig. 47. Failure following undercut of butt weld on outside of angle.

welds could be made which were apparently stronger than the parent metal in that fatigue failure did not take place in the butt weld but at some small distance from it, but that, nevertheless, the fatigue strength of the welded specimen was lower than that of the unwelded specimen, which is the case also for the present tests as is evident when the results for C21 and C23 are compared with any of the results obtained for continuous unwelded stiffeners.

It now remains for the butt welded specimens made in shipyards to be compared with those made in the laboratory. Specimens O1 to O3, which were supposed to be of different quality, did show that there is a difference between O1, which failed after 1,747,800 cycles, and the other two which failed after 906,320 cycles and 1,188,560 cycles respectively. There is, however, no significant difference between these last two, in fact the figures for the number of cycles to failure are in the reverse order to that which was to be expected, because O3 was supposed to be a butt weld of worse quality than O2. Considering specimen O1 alone, this is very much superior to the first series of butt welds made in the laboratory and compares well with those specimens which had been made in the laboratory with a hydrogen controlled electrode. Even the average of these three tests, which is 1,280,890 cycles, is better than that obtained for the first series of laboratory made specimens and considering that two of the specimens incorporated intentionally bad welds, this average does not compare unfavourably even with the machined butt welds made with hydrogen controlled electrodes.

The four other specimens P1 to P4 made in a different shipyard are quite evidently not nearly as good. Specimens P1 and P2 failed after 711,320 cycles and 439,000 cycles respectively, giving an average of 575,160 cycles. The other two specimens, which were meant to be of worse quality, failed after 505,040 cycles and 341,840 cycles respectively, giving an average of 423,440 cycles. The total average for these four specimens is 499,300 cycles, and this is not so good a result as that of the other butt welded specimens tested. The fact that there should be such a difference in the life of butt welded specimens made in different shipyards is difficult to explain. Two of the specimens of type O failed more or less through the centre of the butt weld as is shown in Fig. 48. The third specimen, O2, failed along the undercut of the butt weld as is shown in Fig. 49. It will be seen from these two illustrations that the weld contour is smoother in specimen O1 than in specimen O2. The weld contour of the specimens P was similarly rippled to that of O2 and all these specimens of type P failed similarly to O2, along the undercut of the butt weld.

If all specimens O had failed along the undercut of the butt weld and all specimens P through the centre of the weld, it might have been assumed that the fatigue strength of the weld metal itself was higher for specimens O than it was for specimens P. Whilst it is likely that specimens O and specimens P were welded with different electrodes, the fact that specimens O failed through the centre of the weld and specimens P along the undercut makes the possible explanation of this difference in fatigue strength as being due to the difference in fatigue strength of the weld metal appear doubtful. It is generally assumed that fatigue failures along the undercut of welds are due to the notch effect, but this was evidently not more severe in specimens of type P than it was in specimens of type O. The only remaining possibility to explain this difference in behaviour is perhaps somewhat remote, but it could be that the particular combination of parent metal and weld metal in specimens of type P gave rise to micro-cracks in the transition zone between weld metal and parent metal, which made this zone a plane of weakness.

It is interesting to compare the effect of a butt weld on the fatigue strength of these specimens with the effect of drilled holes. Two specimens called M1 and M2, supplied by another shipyard, were continuous unjointed stiffeners with two plain holes in the flange as shown in Fig. 22. One of these, M1, had a crater in one of the stiffeners where apparently a welded-on distance bar had been chiselled off. These two specimens when tested at ± 8 tons per sq.in. failed after 513,080 and 401,900 cycles. In both cases the failure started from the edge of the hole as is shown in Fig. 50. If these figures are taken to represent the fatigue strength of stiffeners in riveted ships, they indicate that even a bad butt weld does not necessarily reduce the fatigue life of stiffeners to below the limit that would be normally expected in riveted stiffeners.

Specimens Reinforced with Straps.—The results obtained with the specimens having rectangular shaped straps and diamond shaped straps were disappointing in view of the very great care with which the fillet welds connecting these straps had been machined. It has already been pointed out that in the case of the specimens of type D and E two series of specimens were tested under different testing conditions. Specimens D1 and D2 failed after 389,760 and 470,000 cycles when tested at ± 8 tons per sq.in. at the point of maximum stress concentration. Both these specimens failed as did all the other specimens of this type by fatigue cracks starting from the toe of the fillet weld as shown in Figs. 51 and 52. These cracks started at the transition zone between weld metal and parent metal as is shown in Fig. 53, which is a macro section through one of these welds. A hardness survey of this specimen, Fig. 54, shows that the fatigue crack starts in an area where the hardness is higher than in the immediately adjoining parent metal and it is possible that this sudden change in hardness is an additional reason for the fatigue crack starting in this area, quite apart from the stress concentrations.

The lives of the specimens D11 and D12 were even shorter than those of D1 and D2 for the same stress range: 379,340 and 155,280 cycles respectively, which is an average of 267,310 cycles as compared with an average of 429,880 cycles for specimens D1 and D2. The average for D11 and D12 would, of course, be expected to be lower because the stress at the point of stress concentration for these two specimens is greater than in specimens D1 and D2 in consequence of the somewhat higher loading. A similar relationship, only more obvious, has been found for the specimens D3 and D4, and D13 and D14 tested at ± 6 tons per sq.in.

Better results were obtained with the diamond-shaped straps. Specimens E1 and E2, which can be compared with

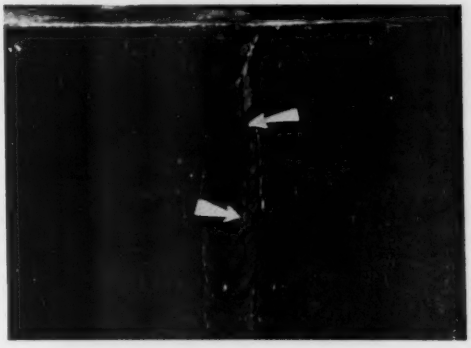


Fig. 48. Failure through butt weld in Specimen O1.

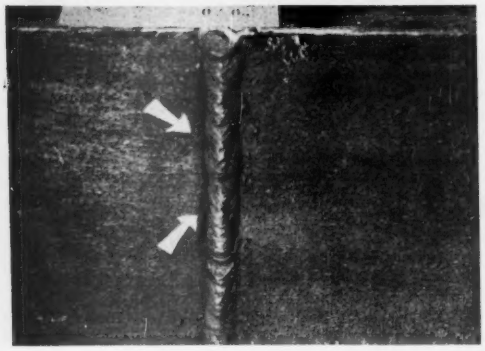


Fig. 49. Failure along undercut in specimen O2.

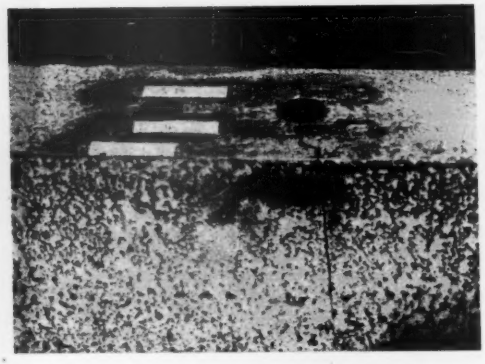


Fig. 50. Failure of specimen M1.

Fig. 51. Failure of specimen D2.

specimens D1 and D2, sustained 860,460 and 669,780 cycles respectively, which is an average of 765,120 cycles compared with 429,880 cycles for D1 and D2. Very much longer lives were also obtained for E3 and E4 in comparison with D3 and D4. Most surprising, however, were the results obtained for E11 and E12 which can be compared with D11 and D12 on the one hand and with E1 and E2 on the other hand. These two specimens failed after 2,108,100 and 2,214,920 cycles which give an average of 2,161,510 cycles compared with 765,120 cycles for specimens E1 and E2. It was expected that the lives of the specimens E11 and E12 would be shorter than those of E1 and E2, in the same way as the lives of specimens D11 and D12 were shorter than those of D1 and D2, because of the somewhat higher loading and the higher stress concentration. The unexpected result can be accounted for by the fact that specimens E11 and E12 had been sculptured with very much more care than the earlier series E1 and E2. Moreover, the machining of the fillet welds in the specimens D1 to D4 and E1 to E4 was done with a high speed pneumatic grinder whilst specimens E11 to E14 were machined with a rotary file. It is well known, of course, that grinding marks have a deleterious effect on fatigue strength and, presumably, the full benefit of machining welds is not realised if this is done by grinding, but it can be realised if the machining is done with a rotary file.

Specimens E1 and E2 both failed by fatigue cracks starting at the toe of the fillet weld as shown in Fig. 55. Similar failures occurred in specimens E11 and E12, the latter being shown in Fig. 56. Specimens E3, E4 and E11 did not fail at the toe of the fillet weld, but at the point where the edge of the strap crossed the heel of the angle. Specimen E13 did not fail in the stiffeners at all but failed in the plating starting from one of the intermittent fillet welds. One specimen, E14, failed right through the centre of the strap as shown in Fig. 57. The crack in this case started on the underside of the strap at the end of the fillet weld in front of the butt weld.

The series of tests D and E showed that the diamond-shaped strap is much better than the rectangular shaped strap, which is in agreement with the results of other investigations. In order to compare the results of these tests with those obtained for butt welds, only D11 to D14 and E11 to E14 can be considered to establish a true comparison. The rectangular strap is seen to be no reinforcement under fatigue conditions, because all four tests with specimens D11 to D14 gave results inferior to those obtained with butt welds, including those obtained for specimens P which were the lowest figures for butt welds of the whole series.

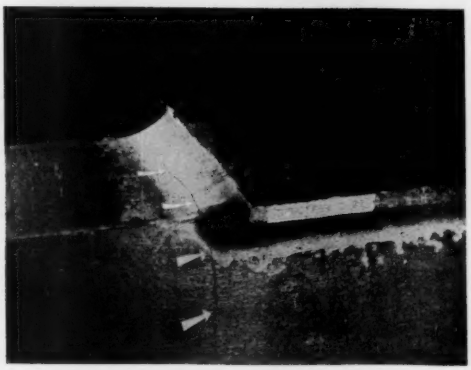


Fig. 52. Failure of specimen D21.

Fig. 53.—Macrosection of specimen D2 after fracture.

The diamond-shaped strap, on the other hand, provided this is as carefully filed as those of specimens E11 to E14 were, is seen to be a very effective reinforcement, especially of butt welds which are not of very high quality.

It was obvious, however, from the beginning of this investigation that straps which would require to be so carefully machined could not possibly be adopted as a practical means of reinforcing butt welds in shipyards. It was necessary, therefore, to investigate other possibilities of reinforcing butt welds or of making joints in stiffeners.

Specimen F which had been made by simply bridging the unwelded gap in the stiffeners with a strap, failed after 46,260 cycles. Not much better were the results obtained with specimen G1 which failed after 87,280 cycles at the end of the strap. This failure is shown in Fig. 58. Specimen G2, which had been slightly modified by grinding the end of the strap, sustained slightly more cycles, 270,240, but also failed at the end of the strap as shown in Fig. 59. This type of strap could, therefore, not be considered an effective reinforcement since it lowers the life of the specimen in terms of cycles much below that obtaining for the plain butt weld.

Much better results were obtained with the Gardiner strap. The first pilot specimen K1 sustained 757,110 cycles. The specimens K11 and K12 sustained 408,460 and 882,180 cycles respectively, which is an average of 645,320 cycles. Specimens K21 and K22 sustained 687,380 and 1,384,740 cycles respectively, which is an average of 1,036,060 cycles. All these specimens of type K failed by cracks developing at the heel of the angle at the end of the fillet weld as is shown in Fig. 60. The specimens of type K21 and K22 which had a more pointed strap are somewhat better than those with 45 deg.

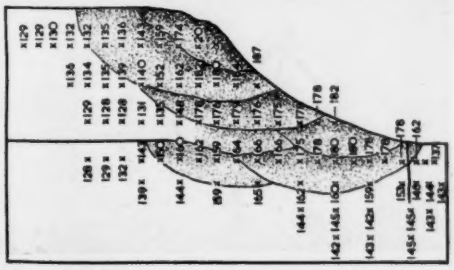


Fig. 54. Hardness survey of specimen D2 (V.P.N./30 kg.).

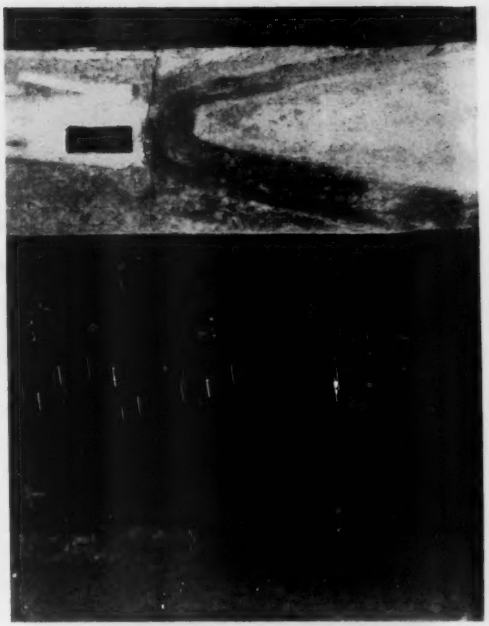


Fig. 55. Failure of Specimen E1.

straps and this type of strap can be considered to be an effective reinforcement of bad butt welds. Good butt welds, however, such as those made with hydrogen controlled electrodes, are not likely to be improved by putting straps on even if they are of this type. The average for specimens C21 to C24 was 1,700,050 cycles and for specimens O1 to O3 it was 1,280,090, whilst the average for specimens K21 and K22 was 1,036,060 cycles. If, however, the butt welds were of the type incorporated in specimens P, for which the average was only 499,300 cycles, the Gardiner strap must be considered as an effective reinforcement. It compares favourably with present practice in shipyards which is represented

by the specimens L1 to L4. The four values for these specimens give an average of 387,950 cycles. These straps cannot, therefore, be considered as an effective reinforcement even for the worst type of butt weld. Specimens type L failed along the undercut of the fillet weld connecting the strap as is shown in Fig. 61.

9. CONCLUSIONS

The following conclusions may be drawn from the present limited series of tests:

1. The fatigue strength of unjointed welded stiffeners is highest when the stiffeners are welded on by means of continuous fillet welds.

2. If intermittent welding is used, staggered fillet welding is preferable to chain fillet welding.

3. Scalloping of the stiffeners, at least when the same form of scallop is used as in these tests, is liable to decrease the life of stiffeners considerably in comparison with stiffeners welded on by intermittent staggered fillet welds, and the scallops will reduce the fatigue strength somewhat even in comparison with stiffeners welded on by chain fillet welding.

4. The most dangerous points at which fatigue failures are to be expected in unjointed welded stiffeners are the ends of intermittent fillet welds, the undercut along fillet welds connecting stiffeners to plating and, in the case of scalloped stiffeners, the return fillets.

5. In the case of scalloped stiffeners the fatigue strength of punched stiffeners is slightly lower than that of gas-cut stiffeners subsequently dressed, but in the latter case with the present form of scallop fatigue cracks may start under 45 deg. to the axis of the stiffeners starting from points of stress concentration in the scallop. The hardening associated with punching may prevent the formation of such cracks in punched stiffeners.

6. Unjointed channel stiffeners riveted to the plating withstood a larger number of cycles than stiffeners welded on with continuous fillet welds.

7. Welded joints in stiffeners generally have the effect of

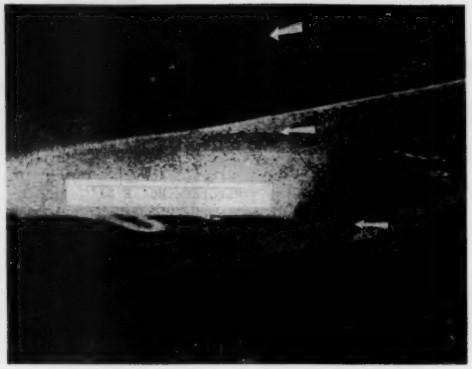


Fig. 56. Failure of specimen E12.

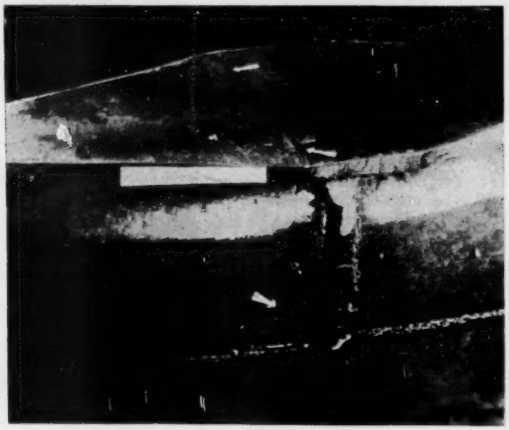


Fig. 57. Failure of specimen E14.

Fig. 58. Failure of specimen G2.

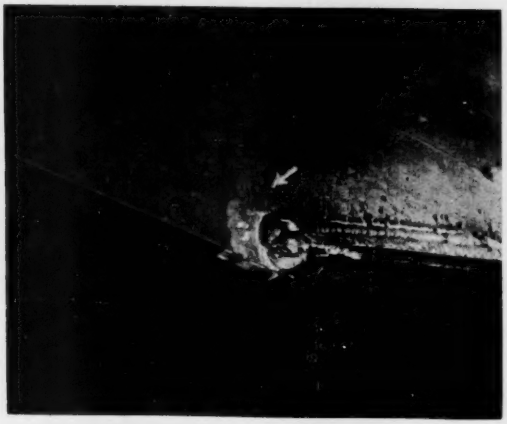


Fig. 59. Failure of specimen G2.

lowering the fatigue strength in comparison with that of unjointed stiffeners. The decrease, however, is not as much for good butt welds as that caused by drilled holes in unjointed stiffeners.

8. The fatigue strength of butt welds in stiffeners depends to some degree on the type of electrode used. Butt welds made with hydrogen controlled electrodes give better values than those made with ordinary electrodes.

9. The removal of the reinforcement of butt welds by grinding does not improve the fatigue strength of butt welds in rolled sections. It is conceivable, however, that if the reinforcement were removed by filing or other methods of machining, an improvement might be obtained.

10. The fatigue strength of butt welds in stiffeners does not appear to be greatly influenced by internal flaws. The results obtained from some of the butt welds made in shipyards, intentionally incorporating flaws, were as good as those obtained from some butt welds made in the laboratory with the greatest care.

11. Of several different types of reinforcing straps for butt welds, the diamond-shaped strap has proved superior to any other type of strap, provided that the fillet welds connecting the strap to the flange are very carefully sculptured with a rotary file to eliminate all traces of undercut and to impart to these fillet welds a smooth concave contour. With such straps some improvement in fatigue life has been obtained, even in comparison with the best butt welds tested.

12. No other type of strap of those tested can be considered an effective reinforcement even for butt welds of low quality, with the exception of the Gardiner strap. This strap is an effective reinforcement for poor quality butt welds. It is recommended that this strap should be made from a 30 deg. isosceles triangle rather than from a 45 deg. isosceles triangle, the former giving a somewhat better performance than the latter.

10. RECOMMENDATIONS FOR FURTHER WORK

Whilst the tests reported on were fairly numerous, the present investigation can be considered as only exploratory. There are a number of questions which have remained unresolved and a number of new problems have arisen from this investigation which sooner or later require solution.

It appeared in this investigation that the effect of machining butt welds does not improve the fatigue strength, which is contrary to all other experimental evidence available. It would be useful to find out whether this fact is due to the grinding operation which has been used in removing the reinforcement or whether it is due to the inherent difficulties of making sound butt welds in rolled sections as distinct from butt welds in plates, for which an increase in the fatigue strength with the removal of the reinforcement has been generally observed in other investigations. In the welding of rolled sections it may be impossible to avoid flaws which can be avoided in plates.

The second problem which clearly requires more careful investigation is the effect of different types of electrodes on the fatigue strength of butt welds. It has quite clearly emerged from the present investigation that the electrode has a noticeable effect on the fatigue strength of the joint. It is also conceivable that the removal of the reinforcement will have a strengthening effect only in butt welds which are made with certain types of electrodes and not with others.

There is, moreover, the interesting phenomenon that specimens in which the butt welds are made with hydrogen controlled electrodes and in which the reinforcement has been removed will fail outside the butt weld, but that the life of the specimen is, nevertheless, as small as that of specimens which fail in the weld and does not nearly attain that which one expects from unjointed specimens. The problem whether

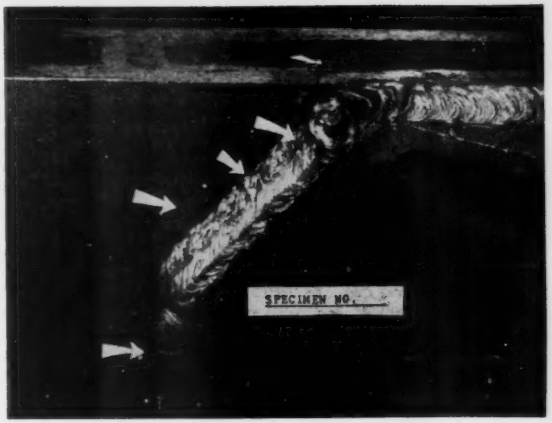


Fig. 60. Failure of specimen K1.

Fig. 61. Typical failure of specimen type L.

there is a zone of weakness from the point of view of fatigue created in consequence of the welding heat at some definite distance from the centre line of the butt weld might be worth looking into.

The fact that one of the specimens failed prematurely through a stray flash at some considerable distance from the point of maximum stress suggests that the effect of stray flashes and possible means of eliminating any deleterious effect should be investigated more fully than has been done hitherto.

In the present investigation it was possible only to determine the relative merits of different types of specimens as expressed in terms of loading cycles. It is desirable on the basis of the data available to carry out some further series of tests with a large number of specimens but a limited number of types, including only those which have been found in this investigation to be both practical in the shipyard and of appreciable fatigue strength, in order to determine the actual fatigue strength for, say, 10,000,000 cycles for these different types.

Since scalloped stiffeners have undoubtedly great practical advantages in shipbuilding it would be useful to develop a form of scallop of a higher fatigue strength than those which have been used in the present investigation.

Whilst the angle stiffener is a popular section for stiffeners

in shipbuilding at present, it is not the only section so used, and it might be useful to carry out two or three series of tests with other types of stiffeners in order to determine whether any one particular section has advantages over other types of section. The particular geometry of the specimen used causes a stress peak to appear at the heel of the angle. Whilst it does not necessarily follow that a panel in a ship stiffened with angle stiffeners and loaded in the ordinary way would give rise to the same sort of stress peak at the heel of the angle, there can be little doubt that a symmetrical section, such as a T-bar for instance, or even a fabricated T-bar, would have a more favourable stress distribution and would, presumably, also show a somewhat higher fatigue strength in consequence.

Finally, it might be useful to have a rather larger number of butt welded specimens made in shipyards in order to arrive at a somewhat more precise estimate of the strength values of shipyard quality butt welds in rolled sections than has been possible to obtain from the limited number of tests carried out in this investigation. It might also be useful to incorporate in an investigation of this type a number of butt welds reinforced with Gardiner type straps of the acute angle variety in order to ascertain more definitely the increase in strength or increase in life which can be obtained by the use of such straps.

APPENDIX

COMPARATIVE FATIGUE TESTS WITH SPECIMENS OF DIFFERENT STIFFNESS BY THE RESONANCE VIBRATION METHOD

When the fatigue endurance of two or several similar components is to be compared, the endurance limit for a given number of cycles—say 2,000,000 or 10,000,000—or for infinite life is determined and this can be expressed either in terms of stress or in terms of load or, more rarely, in terms of deformation. If the components are identical the same answer is generally obtained irrespective of whether the comparison is based on load stress or deformation. If the components are not identical and are only similar in the functional sense, but differ in form and perhaps stiffness, the comparison cannot be based on stress. Only in the comparatively rare case where the deformation of the component in service is limited by definite stops can the comparison be based on deformation.

In general the comparison of similar components of different stiffness must be based on load either by determining the endurance limit or by determining the life in terms of number of cycles for the same load.

In order to compare, for instance, two beams, beam A (Fig. 62a) of uniform cross section with beam B (Fig. 62b) which might be reinforced with two flange plates, it is essential for both beams to be subjected to the same test load. Whilst under static loading conditions it is a foregone conclusion that beam B would be able to carry more load than beam A, this is by no means certain under conditions of repeated loading. In consequence of the stress concentrations at the end of the flange plates in beam B, its endurance limit (that is the maximum load P which it may withstand two million times) may well be smaller than that of beam A or the number of loading cycles when both beams are subjected to repetitions of the same load P may be smaller for beam B than for beam A.

If both beams are subject to the same load the bending moments (Fig. 62 c, d) are identical, but the calculated stresses in beam B will be smaller than in beam A, as is shown in Fig. 62 e, f. In actual fact the stress concentrations at the ends of the flange plates may increase the stress there (Fig. 62h) to a value well above that obtained for beam A.

Supposing now that the fatigue tests were carried out by the resonance vibration method. Consider first beam A. The beam would be supported at its nodes and might have a vibration exciter attached at the centre as shown in Fig. 63.* The vibration exciter produces a force P sin ωt where $\omega = 2\pi n$ and n is the speed of the motor in revolutions per second. If the beam is excited near resonance, that is if n is near the natural frequency of the beam, the loading on the beam is almost entirely inertia loading in comparison with which P sin ωt, which only serves to maintain the vibration, is small.

Consider an element "dx" of the beam at point x (Fig. 64) with mass dm. This element of the beam performs a movement $y = a(x) \sin \omega t$, where $a(x)$ is the amplitude of the beam at point x. The inertia force of the element dx, which is imposed on the beam at point x, is therefore $-a(x)\omega^2 \sin \omega t \, dm$.† Hence the total testing force at any point is proportional—if the beam is of uniform mass—to the amplitude of vibration at that point and the square of the frequency. The maximum testing force applied to the beam is therefore as shown in Fig. 65. There is

(*a*) a distributed load $-(x)_\omega{}^2 dm$ along the beam;

(*b*) a point load at the centre equal to M $a(o)\omega^2$ where M is the mass of the vibration exciter;

and

(*c*) a point load at the centre equal to P, which is comparatively small and not necessarily in phase with the other loads. This load, due to out-of-balance, only serves to maintain the vibration and may be neglected for the present consideration.

In Fig. 66 are drawn the loading, bending moment, and shear diagrams for this beam A, which is of constant cross section.

The diagram of extreme fibre bending stress is obtained from the bending moment diagram by dividing by the modulus of section. The diagram is therefore of similar shape to Fig. 66 and is shown in Fig. 67.

Now consider beam B. Since the mass of the beam is no longer uniform, the natural frequency will be slightly different and the position of the nodes will also be somewhat different. Moreover, the form of the deflection curve will also be slightly different in consequence of the increased stiffness in the centre. Since in practice the second beam would actually be supported at the same distance from the ends as the first beam, we can neglect the change in the position of the nodes.

Since—as was explained—the load is a function of:

(*a*) Amplitude,

(*b*) Mass,

(*c*) Frequency,

and in fact all three quantities are slightly different for beam B, the testing force for this beam will not be exactly the same as for beam A.

This can be seen from the following considerations. Supposing we tested beam B at the same frequency (same speed of the motor) as beam A. Since beam B is stiffer, the conditions for resonance will be different, that is, both natural frequency and position of nodes will alter. The speed of the motor, if it is the same as for beam A, will be further removed from resonance than it was for beam A and we therefore get smaller amplitudes for the same motor speeds.

* For practical purposes (nodal support) a longer specimen must be used if the length between supports (2L) is to be the same. For the sake of clarity, the vibration exciter is assumed to be placed in the centre, whilst most of our work is carried out with an exciter at one end and a balancing mass at the other end. This, however, makes no difference to the argument pursued here.

† The inertia force is mass times acceleration. Since the path of the element is given by $y = a(x) \sin \omega t$, the acceleration is $\frac{dy^2}{dt^2} = -a(x)\omega^2 \sin \omega t$ and hence the inertia force $-a(x)\omega^2 \sin \omega t \, dm$.

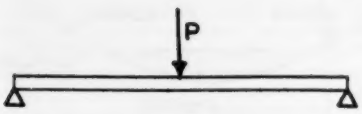


Fig. 62a. Beam A.

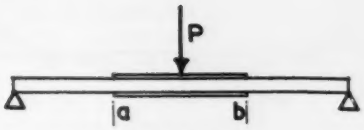


Fig. 62b. Beam B.

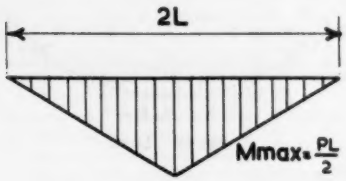


Fig. 62c.

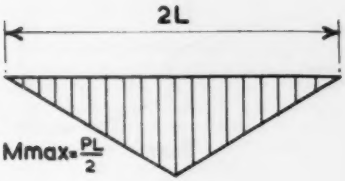


Fig. 62d.

Bending moments.

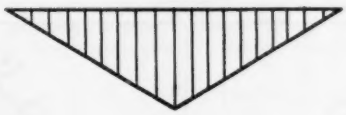


Fig. 62e.

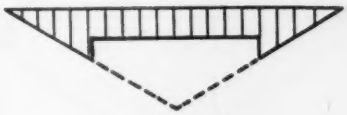


Fig. 62f.

Calculated stresses.

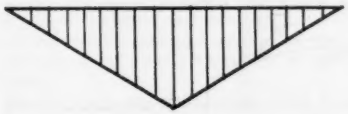


Fig. 62g.

Fig. 62h.

Actual stresses.

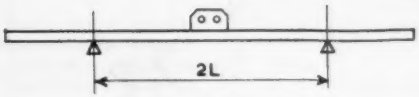


Fig. 63.

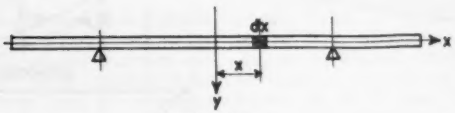


Fig. 64.

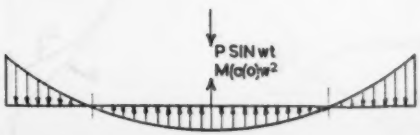
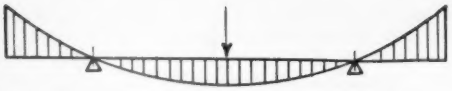
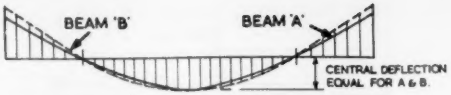


Fig. 65.



Load.



Amplitude.

Shear.

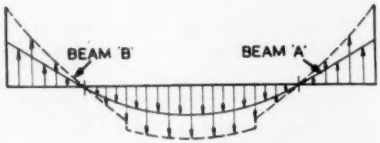


Fig. 69. Load.

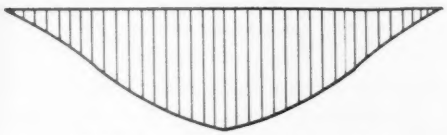


Fig. 66. Bending moment./ Beam A.

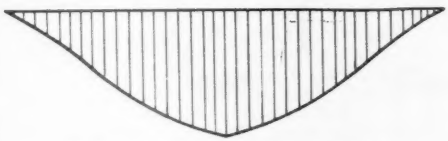


Fig. 67. Extreme fibre stress. Beam A.

Amplitude.

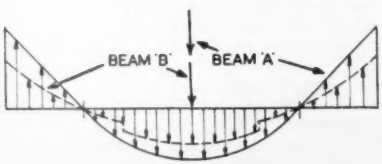


Fig. 68. Load.

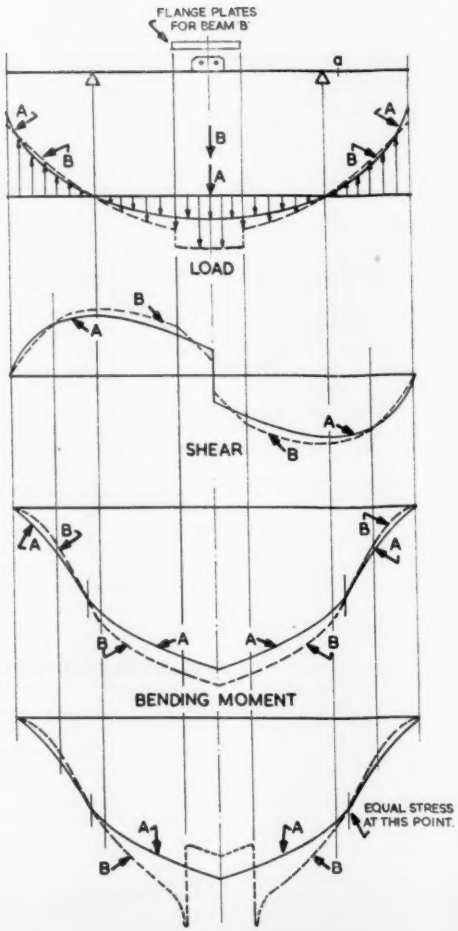


Fig. 70. Extreme fibre bending stress.

This is shown diagrammatically in Fig. 68. Since force is proportional to amplitude and mass, we get the diagram shown in Fig. 68 for the testing force applied to the two beams.

Supposing that instead of testing at the same frequency, we tested at the same central amplitude as beam A, that is, instead of keeping ω constant, we allow it to vary. It is clear that in order to get the same central amplitude in beam B, which is stiffer, we require more force. The larger testing force is derived in part from the larger deflections, away from the centre, from a larger ω and from the larger mass due to the flange plates. This is illustrated in Fig. 69. It follows that irrespective of whether we test at the same amplitude or at the same frequency, the testing force will be slightly different for the two beams if they are tested by the resonance method. This is a direct consequence of the fact that the change in mass and stiffness produces a change in the *distribution* of the inertia force.

Some of the tests in the present series were carried out so that the maximum stress occurring at any point in the beam —even if it was a stress concentration due to the change in section—was kept constant for all types of specimens. This means in practical terms that the testing conditions for the specimens with flange plates are more favourable than for the specimens without flange plates, since a smaller testing force is required to produce a stress of "X" tons per sq.in. at a stress concentration than is required to produce "X" tons per sq.in. at the centre of a uniform beam.

If under these conditions beam B shows a shorter life than beam A, it is obvious that it would show an ever shorter life in comparison with A if the fatigue test had been performed at constant load for both specimens.

Instead of testing beam A at a stress of, say, ± 8 tons per sq.in. at the centre and beam B at ± 8 tons per sq.in. at the end of the flange plates, which is not a fair comparison, one might pick an arbitrary point "*a*" at some distance from the centre of the beam, that is, away from the stress concentration where the stress in beam A is, say, x tons per sq.in. Beam B can then be tested so that the same stress of x tons per sq.in. is realised at the corresponding point in beam B. This does not necessarily mean, however, that if the stress is the same at this point, it is necessarily also the same in both beams at all other points outside the area influenced by the flange plates. This is illustrated in Fig. 70, which shows different curves for loading, shear, bending moment and extreme fibre stress, despite the fact that the stress at point "*a*" is the same for both beam A and beam B.

In the present case, however, of stiffened panels, the mass of the welded-on straps is fairly small in comparison with the mass of the specimen, and whilst the curves for stress and, therefore, for loading will not coincide, the difference is probably so small that it can be ignored.

ACKNOWLEDGMENTS

To carry out an extensive programme of tests on large specimens such as is described in this report cannot be the work of one man. Whilst the author was responsible for the organisation and execution of the tests proper and for the compilation of this report and must be held entirely responsible for the opinions expressed therein, the work could not have been carried out without a great deal of help from many individuals.

In the first place, the author must place on record his indebtedness to Mr. James Turnbull who originally suggested this investigation, and with whom the author collaborated in drawing up the detailed programme of tests and who, throughout the time this investigation was in progress, shared in its direction.

The author is greatly indebted also to Mr. A. Ramsay Moon, former Director of the British Welding Research Association, for giving much help in the planning stage of this investigation and in the difficult task of assembling the facilities which enabled this investigation to be carried out, and to Dr. H. G. Taylor, Director of Research, for giving his support and encouragement to the continuation of this investigation after it had been begun.

The author wishes to express his gratitude also to Professor J. F. Baker, head of the Engineering Department in the University of Cambridge, for much valuable discussion and for making available to the author certain facilities in his department without which this work could not even have been started.

Grateful acknowledgment is due also to Mr. W. G. John and Mr. D. W. Smithers, Department of Naval Construction, Admiralty, through whose good offices the pilot specimen was obtained and who arranged for the radiographic examination of the specimens, and to Mr. L. T. Sayers and his collaborators of the Admiralty Radiography Section for carrying this out.

Dr. E. C. Rollason and Mr. Ralph Baines, of Murex Welding Processes Ltd., very kindly provided assistance in the fabrication of some of the specimens. Mr. Paul Whitaker, of Stewarts & Lloyds Ltd., Corby, must be thanked for having carried out the chemical analysis and the determination of grain size of the material at the Research Laboratories of Stewarts & Lloyds Ltd., Corby.

The author's thanks are due also to the following firms and individuals who supplied some of the specimens:

Mr. E. Cuthbert, Harland & Wolff Ltd., Belfast;

Mr. D. M. Kerr, of Alexander Stephen & Sons Ltd., Glasgow;

Mr. J. Lenaghan, of Wm. Gray & Sons Ltd., West Hartlepool.

Mr. L. Redshaw, of Vickers Armstrongs Ltd., Barrow-in-Furness.

Finally, it is the author's pleasant duty to acknowledge his grateful thanks to his present and former collaborators, Mr. A. T. S. Gardiner and Mr. A. Bodek, who looked after the investigation jointly with the author, to Mr. E. O. Lawrance who made most of the specimens, and to Mr. R. D. Burton, Mr. B. W. Carter, Mr. D. H. Hillman and Mr. P. Pearce, who performed many and varied tasks necessitated in the course of the investigation.

Printed in England by Lawrence Press Ltd. Henry Road, Clow Barnet, Herts